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(12) **United States Patent**
**Friel et al.**

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(45) **Date of Patent: Mar. 8, 2016**

(54) **SYSTEM AND METHOD FOR PERFORMING AUTO-LOCATION OF A TIRE PRESSURE MONITORING SENSOR ARRANGED WITH A VEHICLE WHEEL USING CONFIDENCE INTERVAL ANALYSIS AND CHANGE OF WHEEL DIRECTION**

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(72) Inventors: **Edward Friel**, Belfast (GB); **Gary Graham**, Co. Antrim (GB); **Peter Walker**, Co. Londonderry (GB); **Alan Millen**, Co. Londonderry (GB)

(73) Assignee: **Schrader Electronics Ltd.**, Antrim (GB)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 83 days.

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(22) Filed: **Nov. 18, 2013**

(65) **Prior Publication Data**

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**Related U.S. Application Data**

(63) Continuation-in-part of application No. 13/973,855, filed on Aug. 22, 2013.

(51) **Int. Cl.**
***B60C 23/04*** (2006.01)
***B60C 23/00*** (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ............. ***B60C 23/0488*** (2013.01); ***B60C 23/00*** (2013.01); ***B60C 23/0416*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC B60C 23/00; B60C 23/0488; B60C 23/0416; B60C 23/0489; B60T 8/171; B60T 8/172; B60W 40/10; G01P 13/045
USPC ........................................................ 701/34.4
See application file for complete search history.

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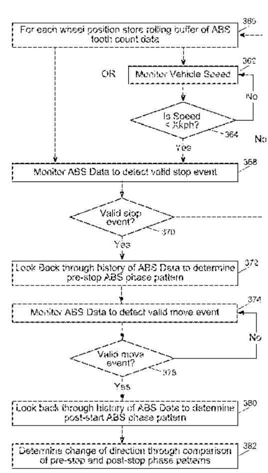
(57) **ABSTRACT**

A method for determining change of direction of a vehicle includes steps of maintaining a rolling window of ABS data indicative of ABS tooth count and capturing a relevant rolling window of ABS data at the predetermined one-measurement point; storing the rolling window of the ABS data indicative of ABS tooth in a buffer; monitoring the ABS data and detecting a valid stop event which causes the rate of change of ABS tooth count to substantially decrement to zero; and monitoring the ABS data and detecting a valid move event which causes the rate of change of ABS tooth count to substantially increment from zero. The method also includes steps of determining a pre-stop phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately prior to the valid stop event; determining a post-start phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately subsequent to the valid move event; and correlating the pre-stop phase relationship and the post-start phase relationship to determine change of direction and confidence level.

**20 Claims, 48 Drawing Sheets**



(51) **Int. Cl.**
***B60T 8/171*** (2006.01)
***B60T 8/172*** (2006.01)
***B60W 40/10*** (2012.01)
***G01P 13/04*** (2006.01)

(52) **U.S. Cl.**
CPC ............. ***B60C23/0489*** (2013.01); ***B60T 8/171*** (2013.01); ***B60T 8/172*** (2013.01); ***B60W 40/10*** (2013.01); ***G01P 13/045*** (2013.01)

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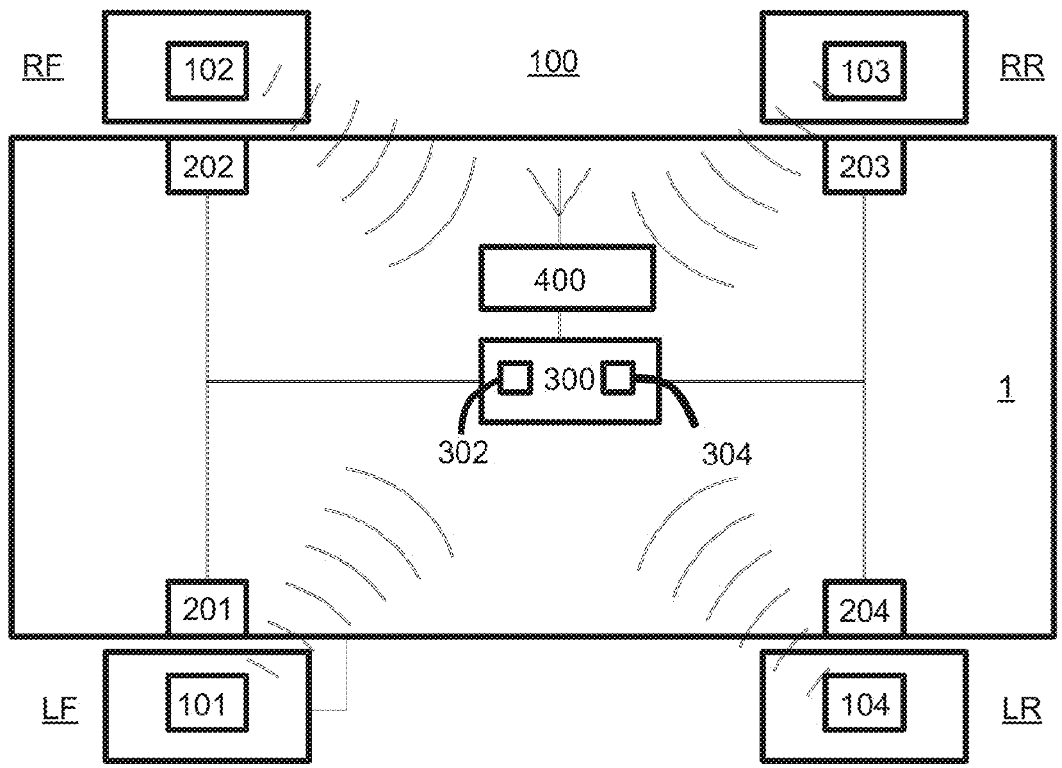



Figure 1

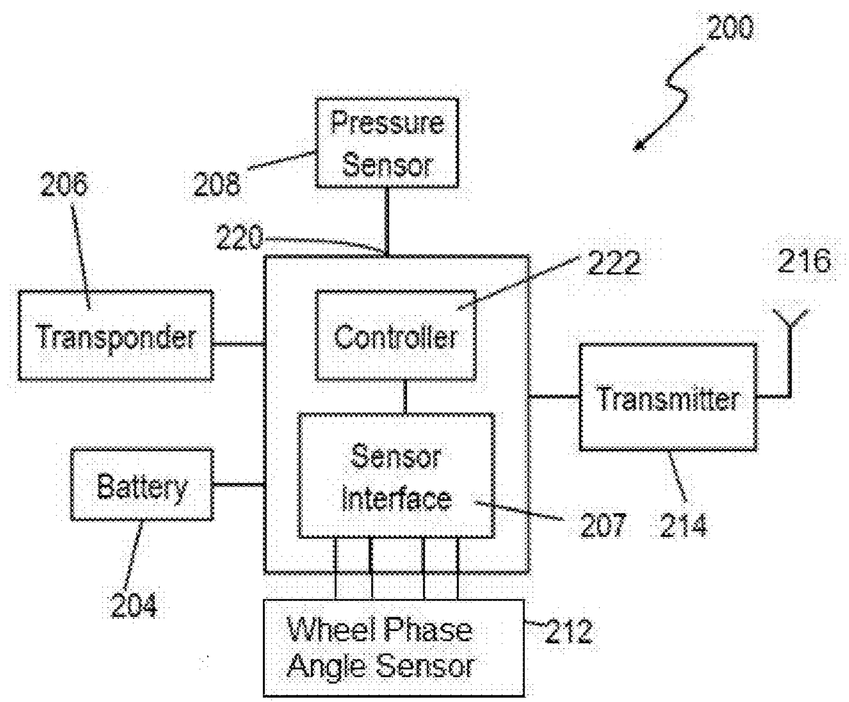

200
Pressure Sensor
208
206
220
222
216
Transponder
Controller
Transmitter
Sensor Interface
Battery
207
214
204
Wheel Phase Angle Sensor
212

Figure 2

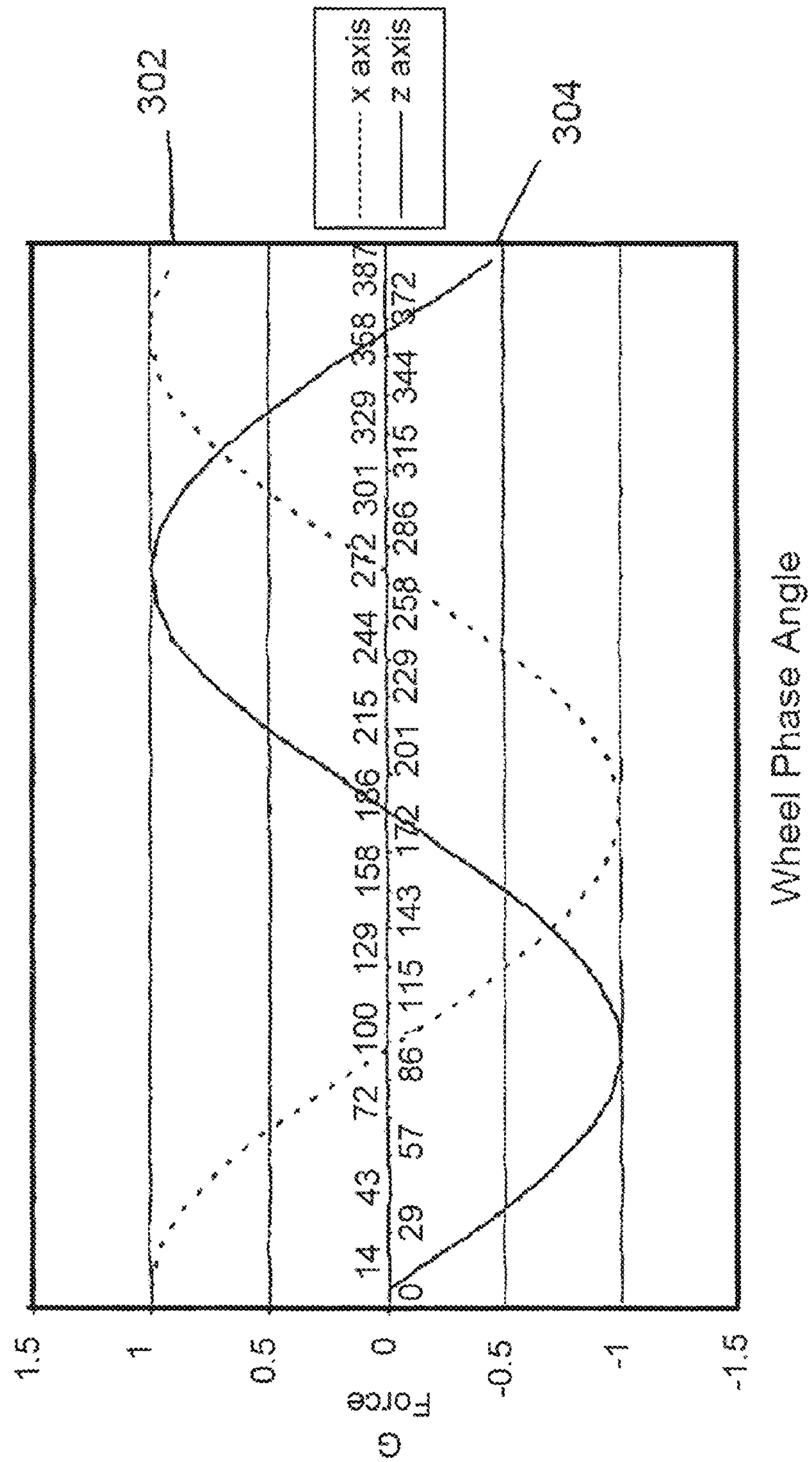

302
304
x axis
z axis
Wheel Phase Angle
G Force
1.5
1
0.5
0
-0.5
-1
-1.5
0 14 29 43 57 72 86 100 115 129 143 158 172 186 201 215 229 244 258 272 286 301 315 329 344 358 372 387

Figure 3A

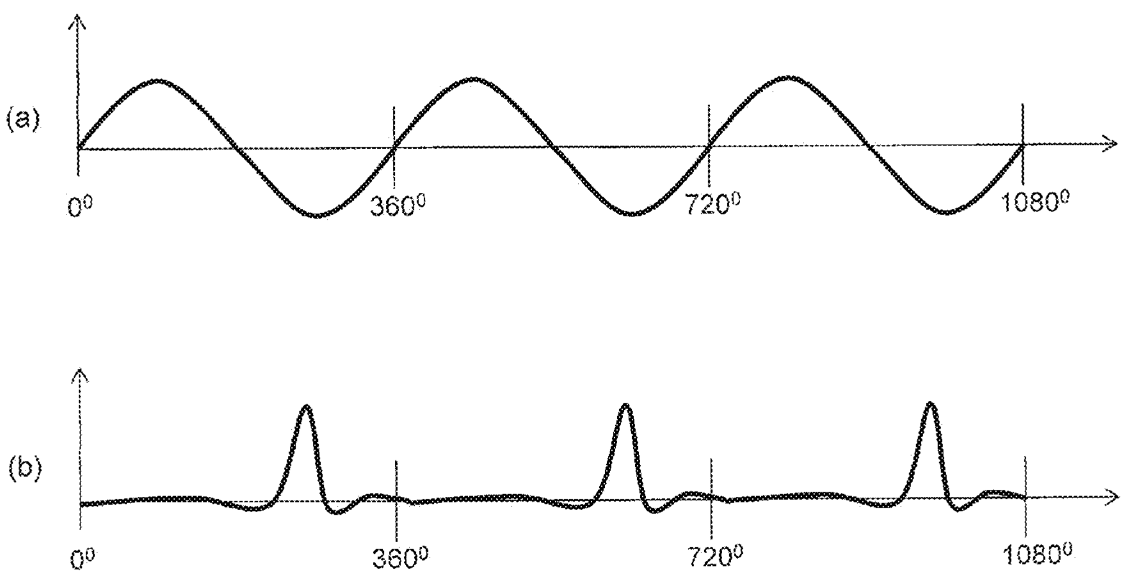



Figure 3B

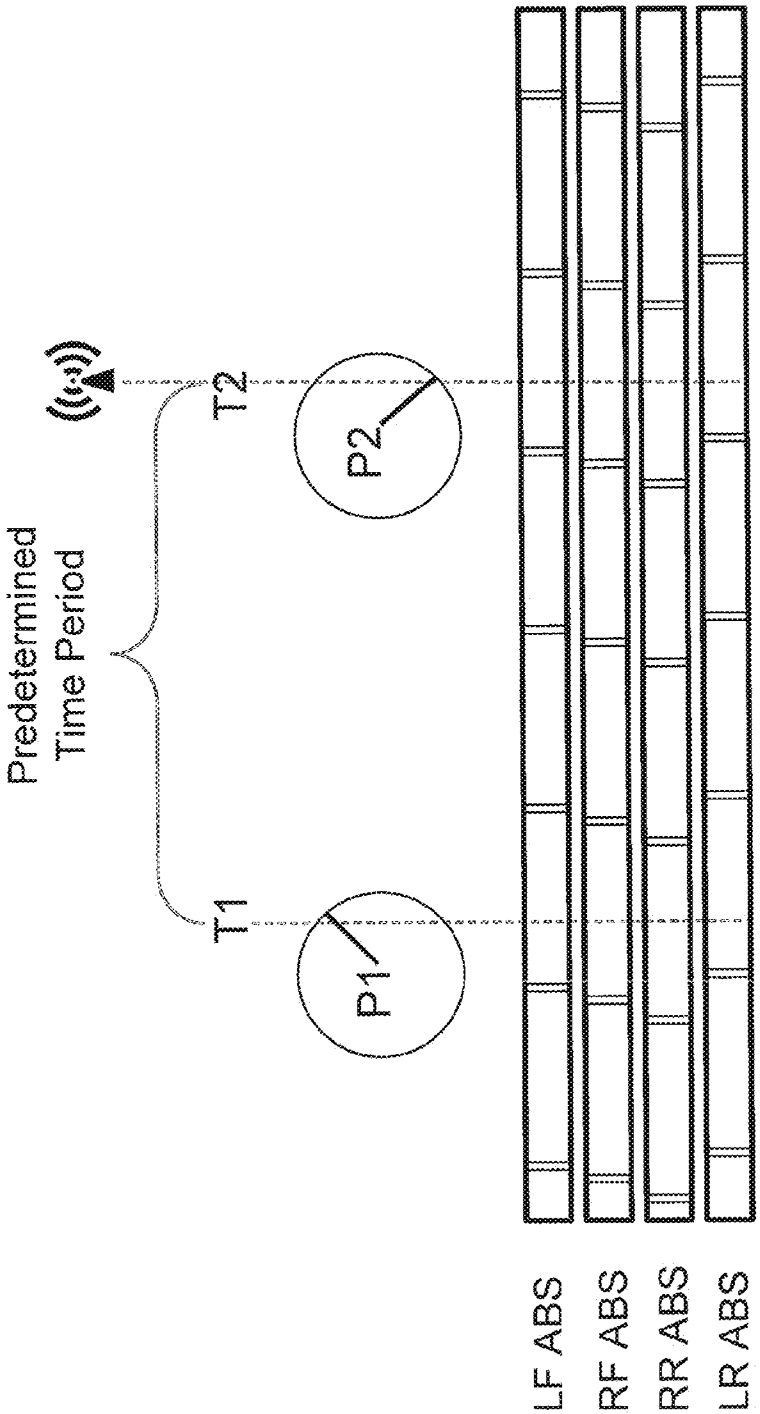
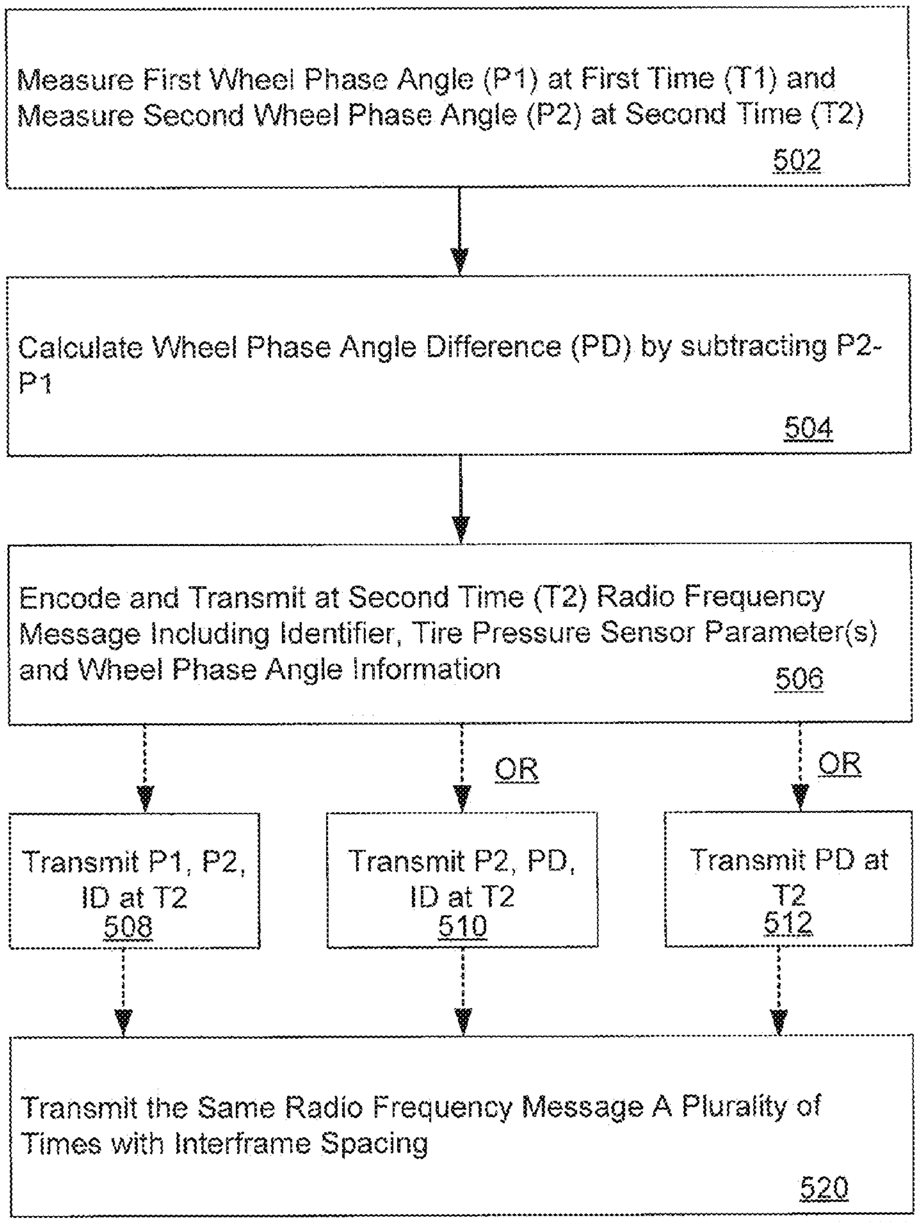

Predetermined
Time Period
T1
T2
P1
P2
LF ABS
RF ABS
RR ABS
LR ABS

Figure 4



Measure First Wheel Phase Angle (P1) at First Time (T1) and Measure Second Wheel Phase Angle (P2) at Second Time (T2)
502
Calculate Wheel Phase Angle Difference (PD) by subtracting P2-P1
504
Encode and Transmit at Second Time (T2) Radio Frequency Message Including Identifier, Tire Pressure Sensor Parameter(s) and Wheel Phase Angle Information
506
OR
OR
Transmit P1, P2, ID at T2
508
Transmit P2, PD, ID at T2
510
Transmit PD at T2
512
Transmit the Same Radio Frequency Message A Plurality of Times with Interframe Spacing
520


Figure 5

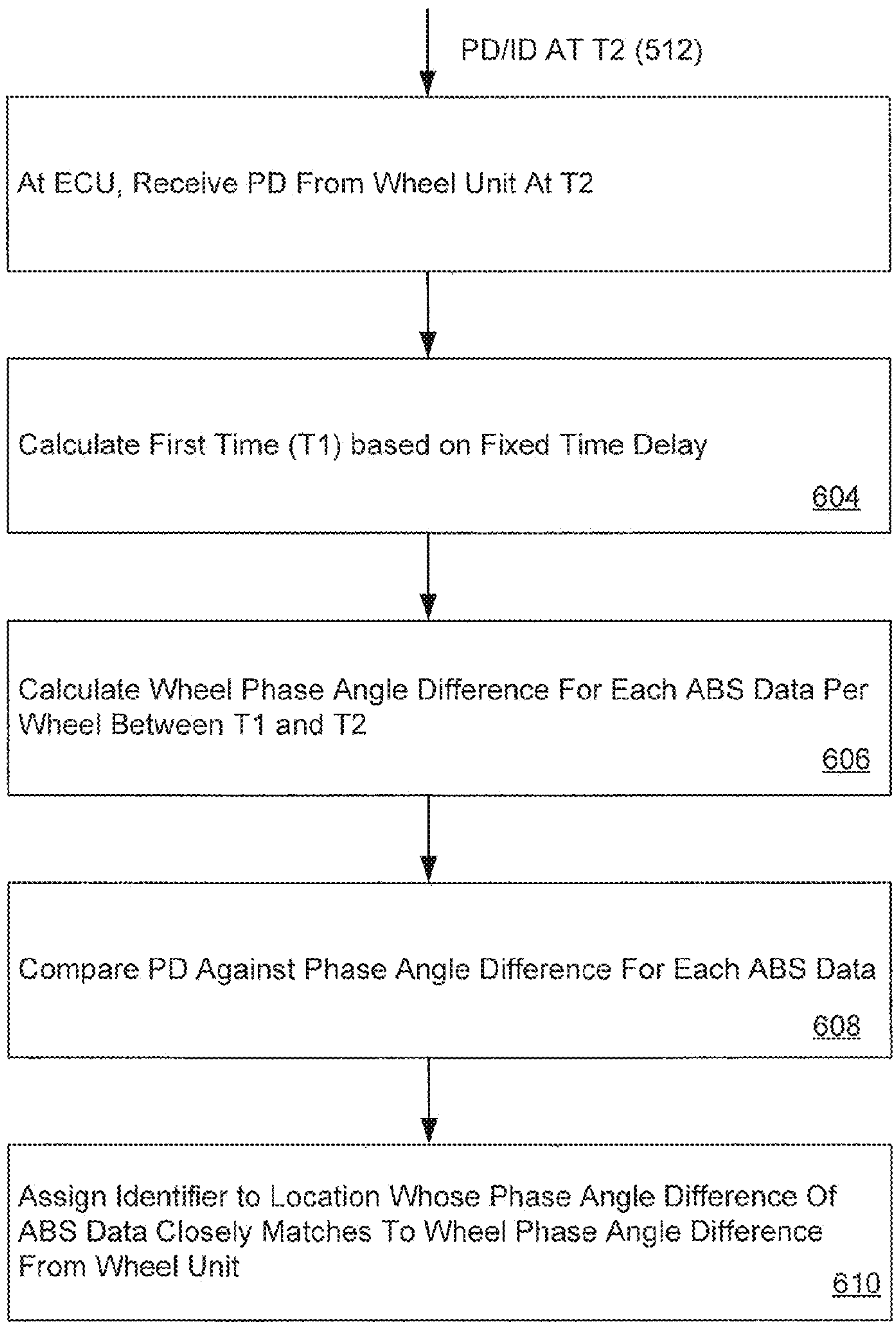

PD/ID AT T2 (512)
At ECU, Receive PD From Wheel Unit At T2
Calculate First Time (T1) based on Fixed Time Delay
604
Calculate Wheel Phase Angle Difference For Each ABS Data Per Wheel Between T1 and T2
606
Compare PD Against Phase Angle Difference For Each ABS Data
608
Assign Identifier to Location Whose Phase Angle Difference Of ABS Data Closely Matches To Wheel Phase Angle Difference From Wheel Unit
610

Figure 6

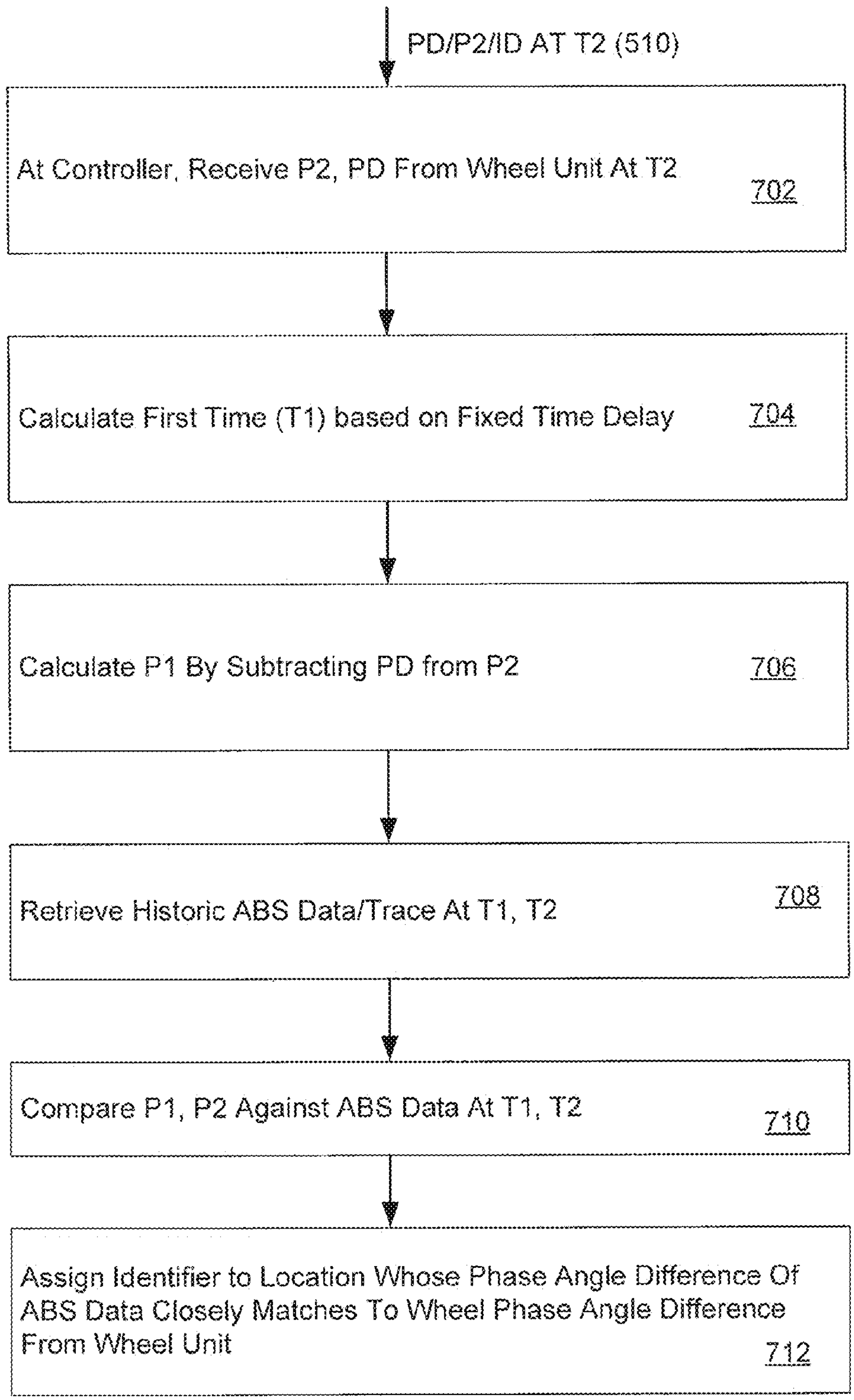

PD/P2/ID AT T2 (510)
At Controller, Receive P2, PD From Wheel Unit At T2
702
Calculate First Time (T1) based on Fixed Time Delay
704
Calculate P1 By Subtracting PD from P2
706
Retrieve Historic ABS Data/Trace At T1, T2
708
Compare P1, P2 Against ABS Data At T1, T2
710
Assign Identifier to Location Whose Phase Angle Difference Of ABS Data Closely Matches To Wheel Phase Angle Difference From Wheel Unit
712

Figure 7

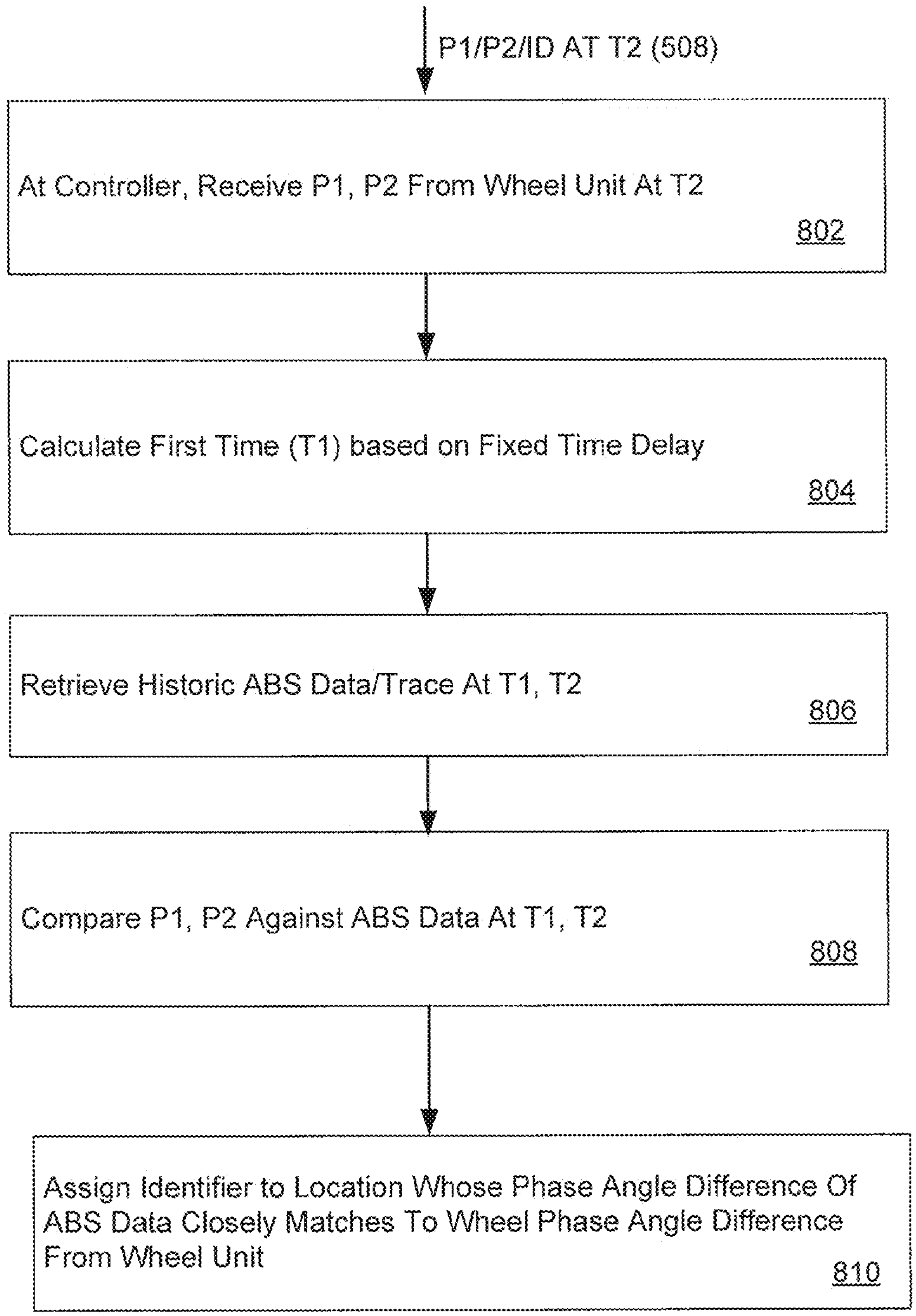

P1/P2/ID AT T2 (508)
At Controller, Receive P1, P2 From Wheel Unit At T2
802
Calculate First Time (T1) based on Fixed Time Delay
804
Retrieve Historic ABS Data/Trace At T1, T2
806
Compare P1, P2 Against ABS Data At T1, T2
808
Assign Identifier to Location Whose Phase Angle Difference Of ABS Data Closely Matches To Wheel Phase Angle Difference From Wheel Unit
810

Figure 8

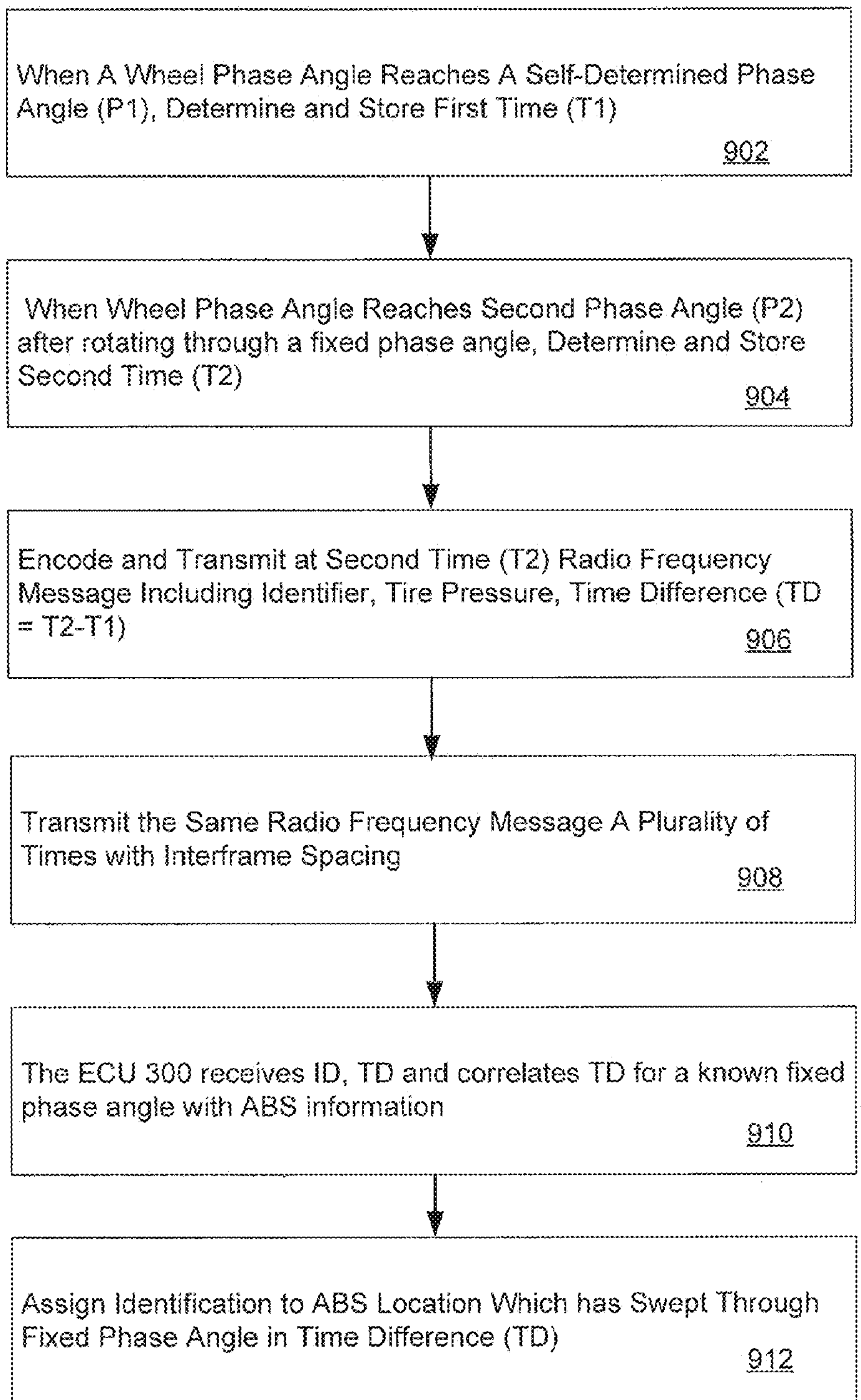

When A Wheel Phase Angle Reaches A Self-Determined Phase Angle (P1), Determine and Store First Time (T1)
902
When Wheel Phase Angle Reaches Second Phase Angle (P2) after rotating through a fixed phase angle, Determine and Store Second Time (T2)
904
Encode and Transmit at Second Time (T2) Radio Frequency Message Including Identifier, Tire Pressure, Time Difference (TD = T2-T1)
906
Transmit the Same Radio Frequency Message A Plurality of Times with Interframe Spacing
908
The ECU 300 receives ID, TD and correlates TD for a known fixed phase angle with ABS information
910
Assign Identification to ABS Location Which has Swept Through Fixed Phase Angle in Time Difference (TD)
912

Figure 9

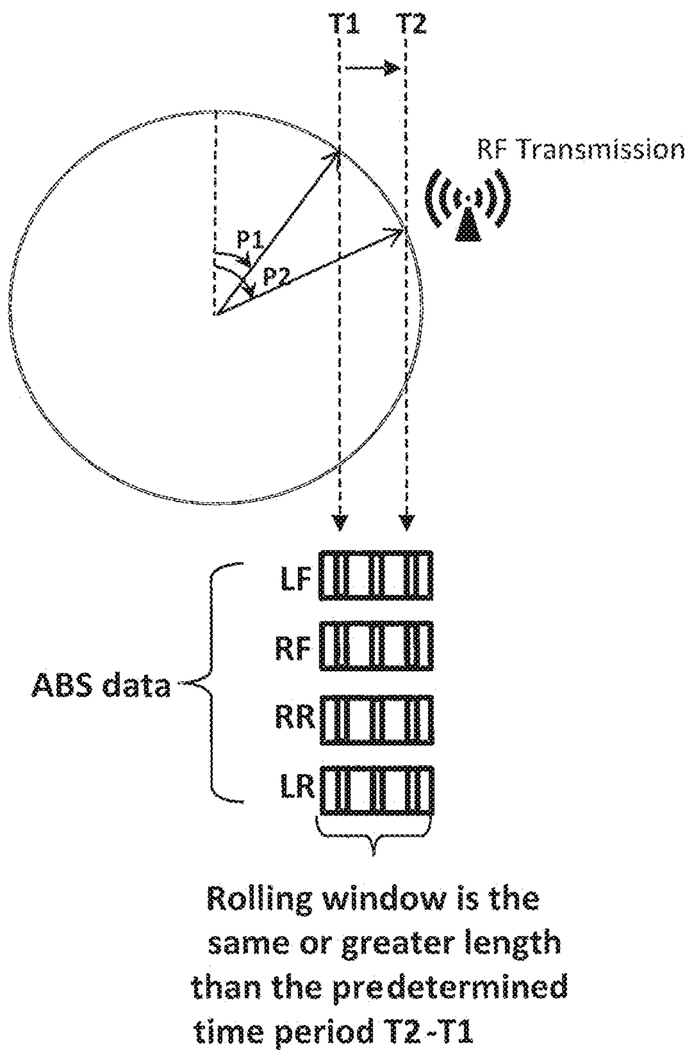

T1
T2
RF Transmission
P1
P2
LF
RF
RR
LR
ABS data
Rolling window is the same or greater length than the predetermined time period T2 -T1

Figure 10A

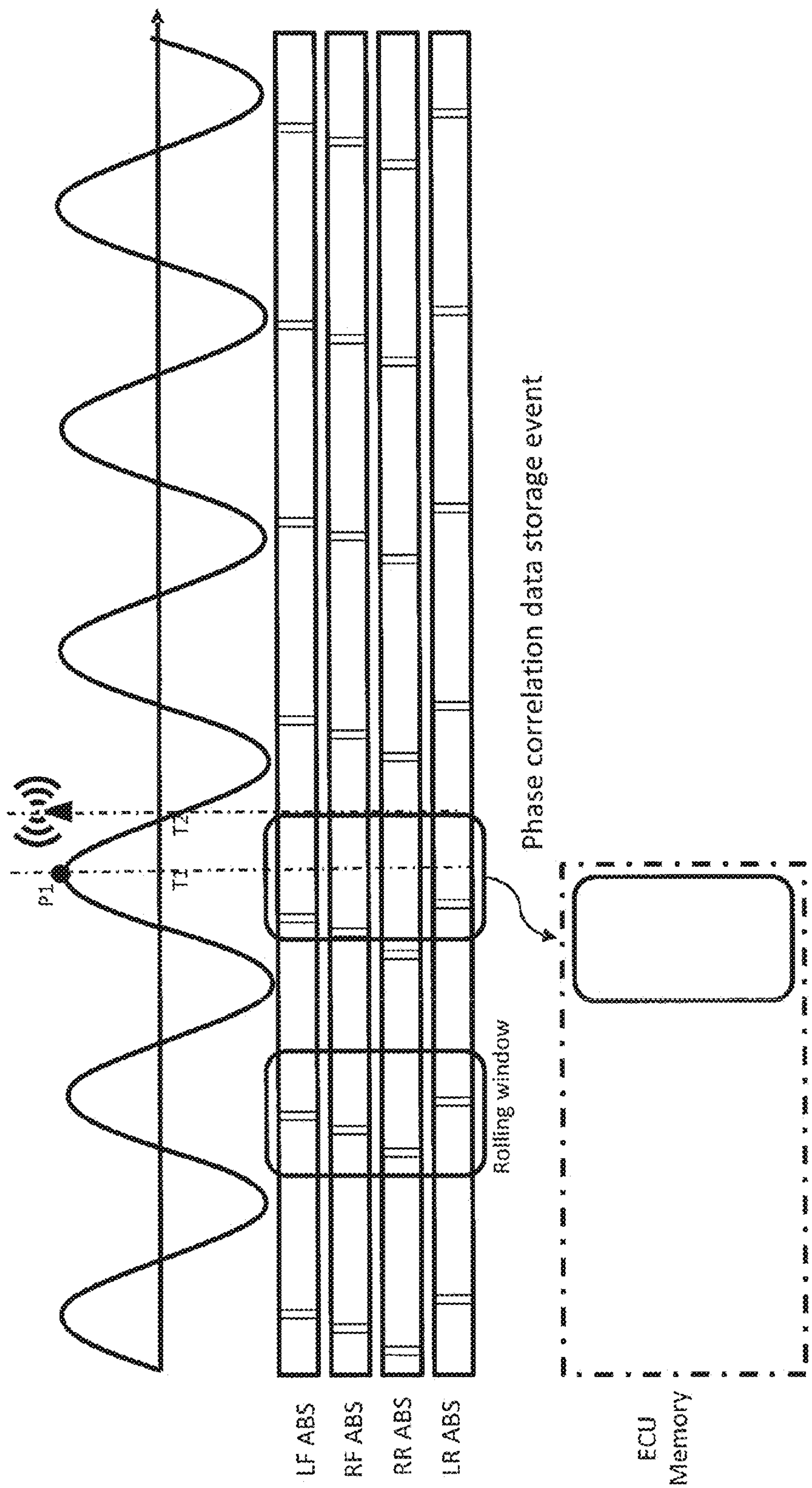

P1
T1
T2
Phase correlation data storage event
Rolling window
LF ABS
RF ABS
RR ABS
LR ABS
ECU Memory

Figure 10B

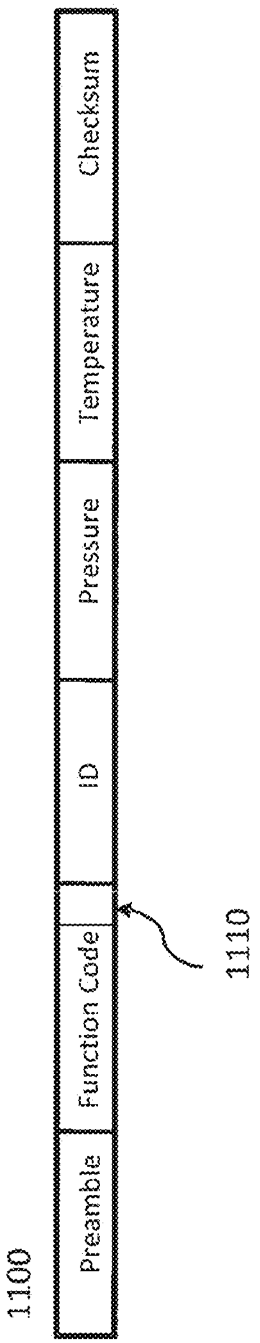



Figure 11A

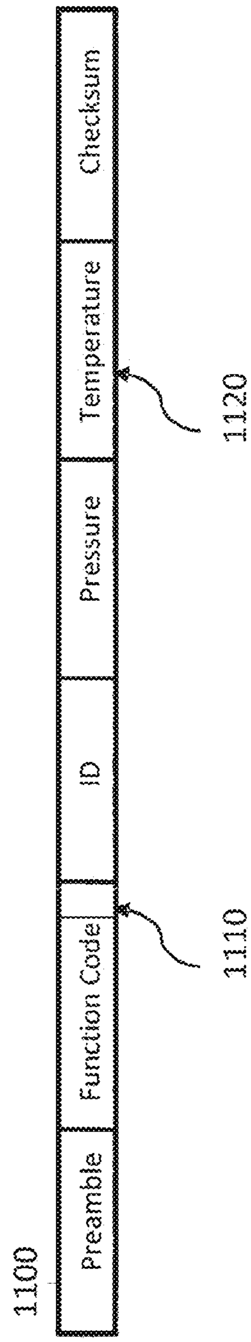



Figure 11B

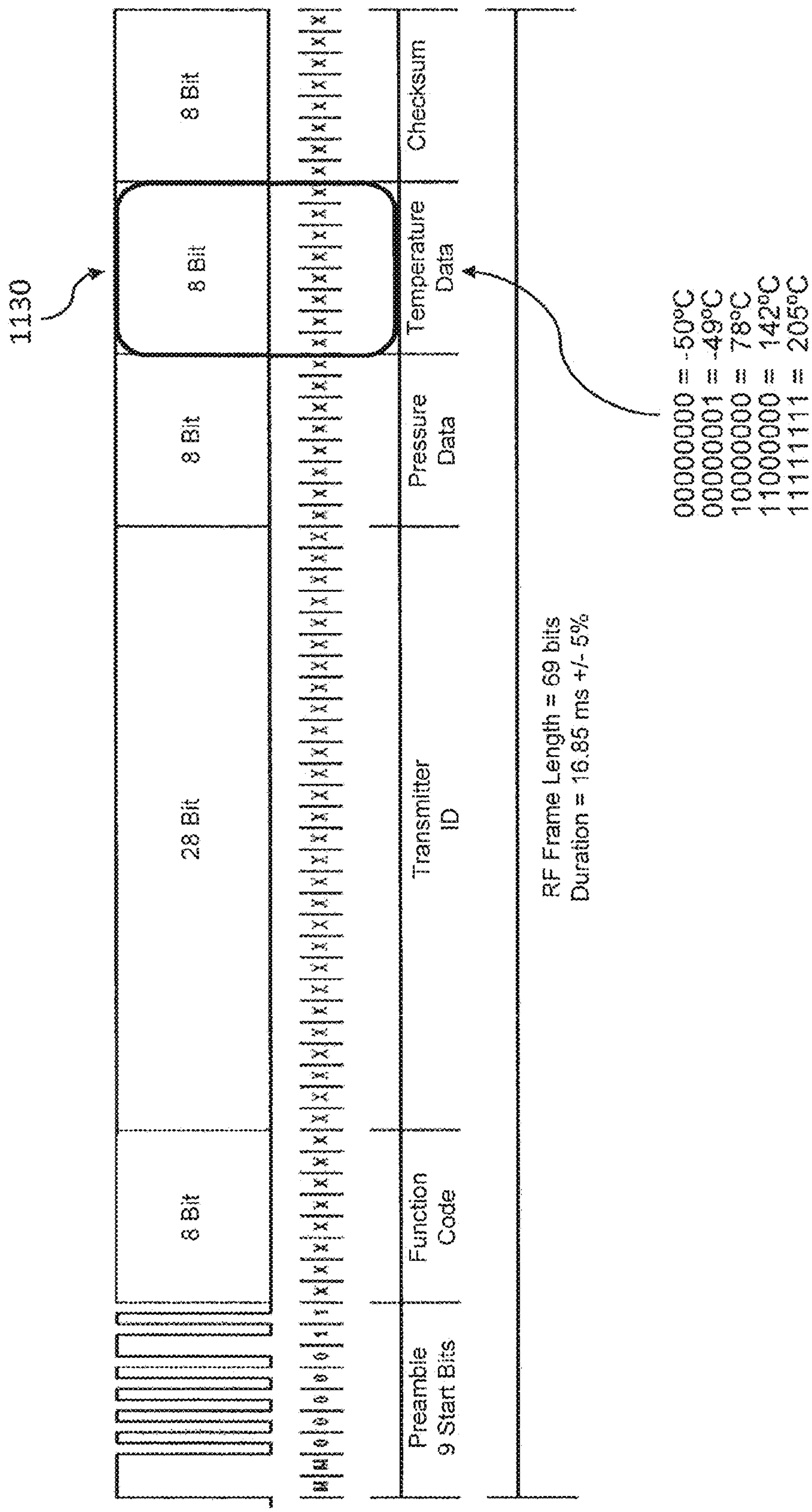

1130
8 Bit
28 Bit
8 Bit
8 Bit
8 Bit
Preamble
9 Start Bits
Function
Code
Transmitter
ID
Pressure
Data
Temperature
Data
Checksum
RF Frame Length = 69 bits
Duration = 16.85 ms +/- 5%
00000000 = -50°C
00000001 = -49°C
10000000 = 78°C
11000000 = 142°C
11111111 = 205°C

Figure 11C

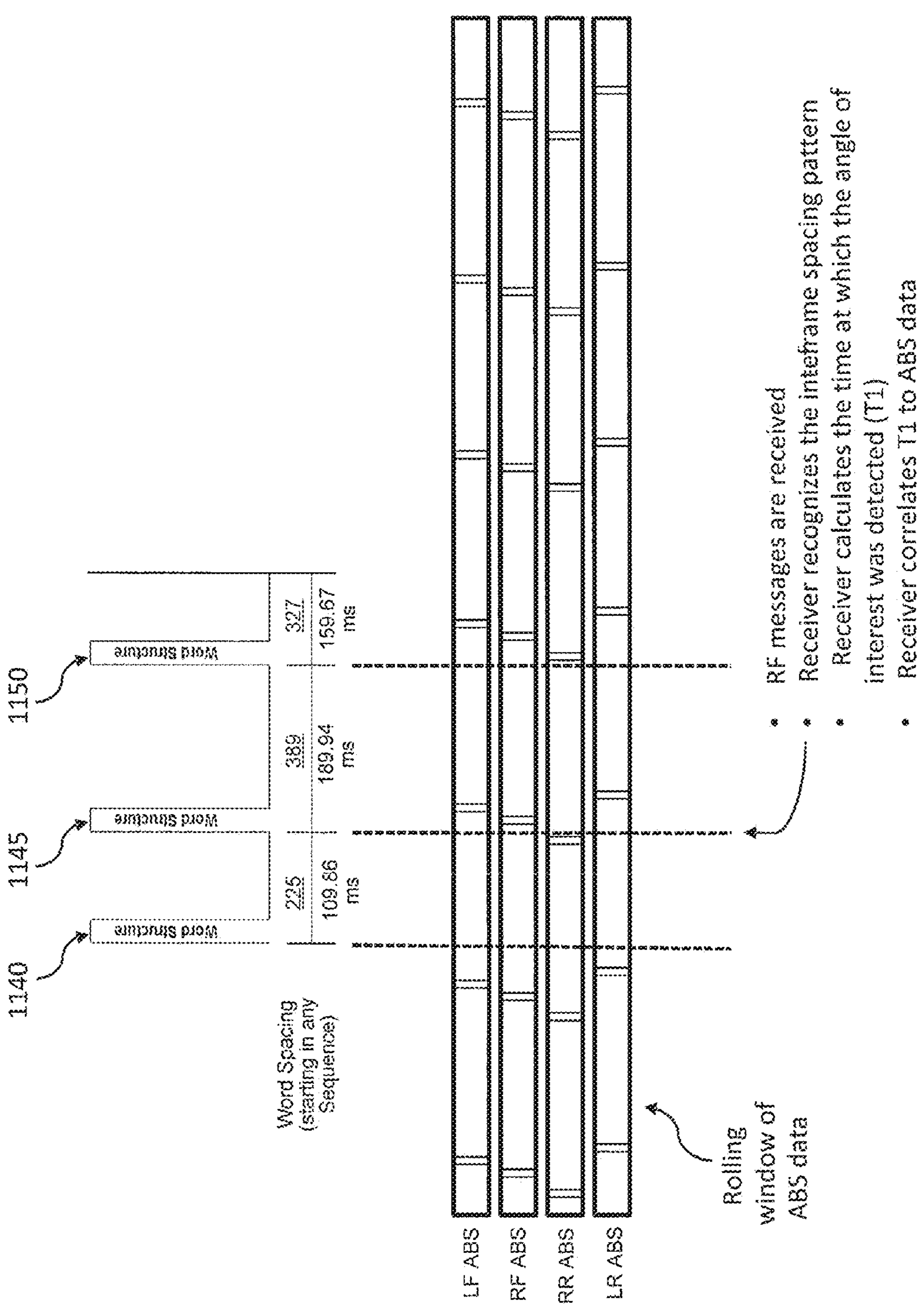

1140
1145
1150
Word Structure
Word Structure
Word Structure
Word Spacing (starting in any Sequence)
225
109.86 ms
389
189.94 ms
327
159.67 ms
LF ABS
RF ABS
RR ABS
LR ABS
Rolling window of ABS data
• RF messages are received
• Receiver recognizes the inteframe spacing pattern
• Receiver calculates the time at which the angle of interest was detected (T1)
• Receiver correlates T1 to ABS data

Figure 11D

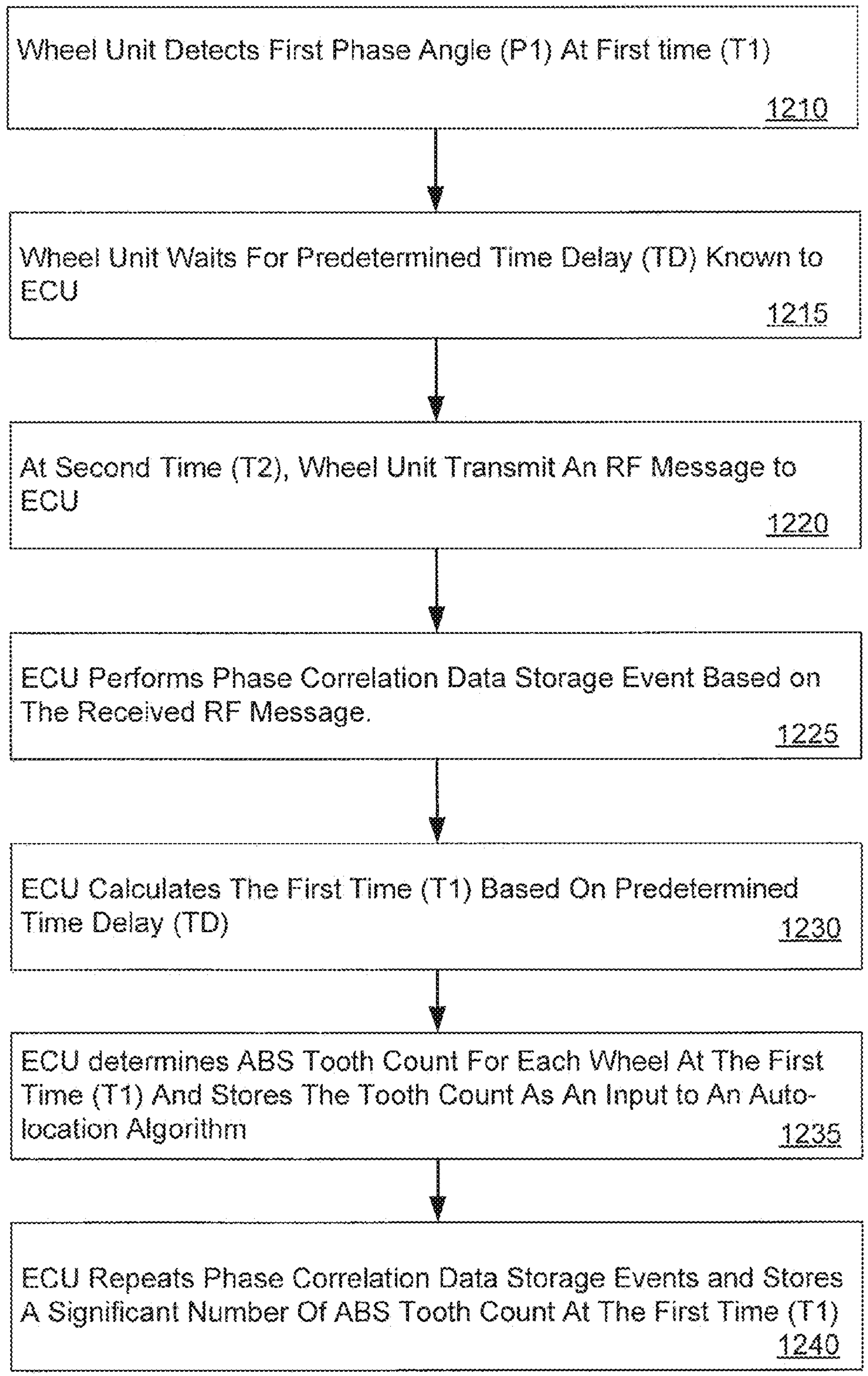

Wheel Unit Detects First Phase Angle (P1) At First time (T1)
1210
Wheel Unit Waits For Predetermined Time Delay (TD) Known to ECU
1215
At Second Time (T2), Wheel Unit Transmit An RF Message to ECU
1220
ECU Performs Phase Correlation Data Storage Event Based on The Received RF Message.
1225
ECU Calculates The First Time (T1) Based On Predetermined Time Delay (TD)
1230
ECU determines ABS Tooth Count For Each Wheel At The First Time (T1) And Stores The Tooth Count As An Input to An Auto-location Algorithm
1235
ECU Repeats Phase Correlation Data Storage Events and Stores A Significant Number Of ABS Tooth Count At The First Time (T1)
1240

Figure 12

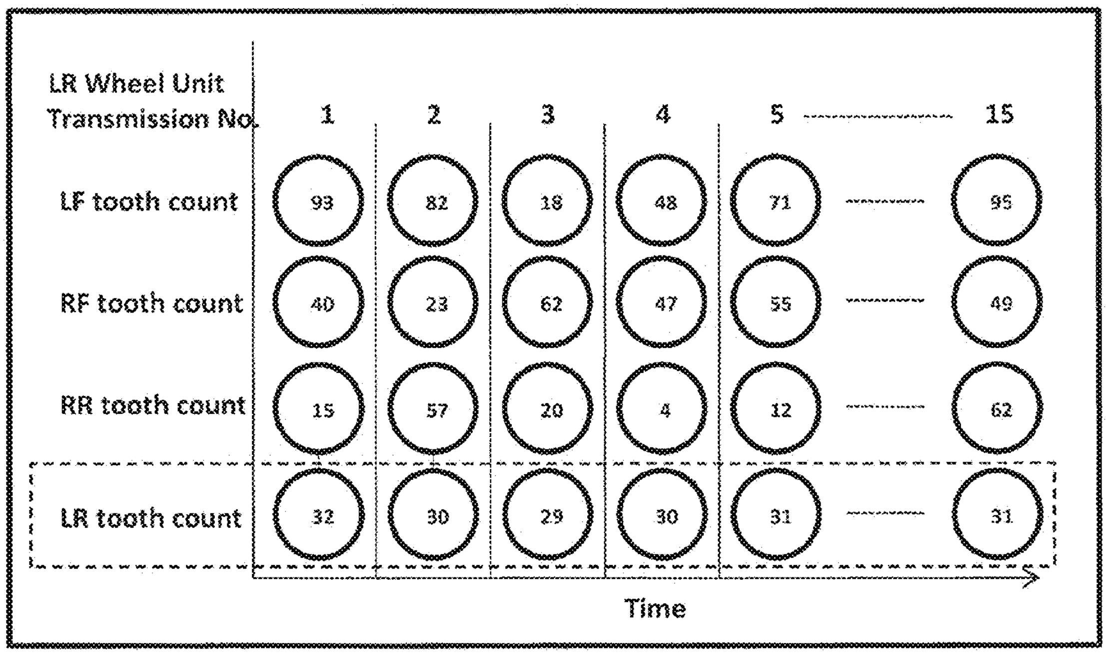

LR Wheel Unit
Transmission No.
1
2
3
4
5
15
LF tooth count
93
82
18
48
71
95
RF tooth count
40
23
62
47
55
49
RR tooth count
15
57
20
4
12
62
LR tooth count
32
30
29
30
31
31
Time

Figure 13

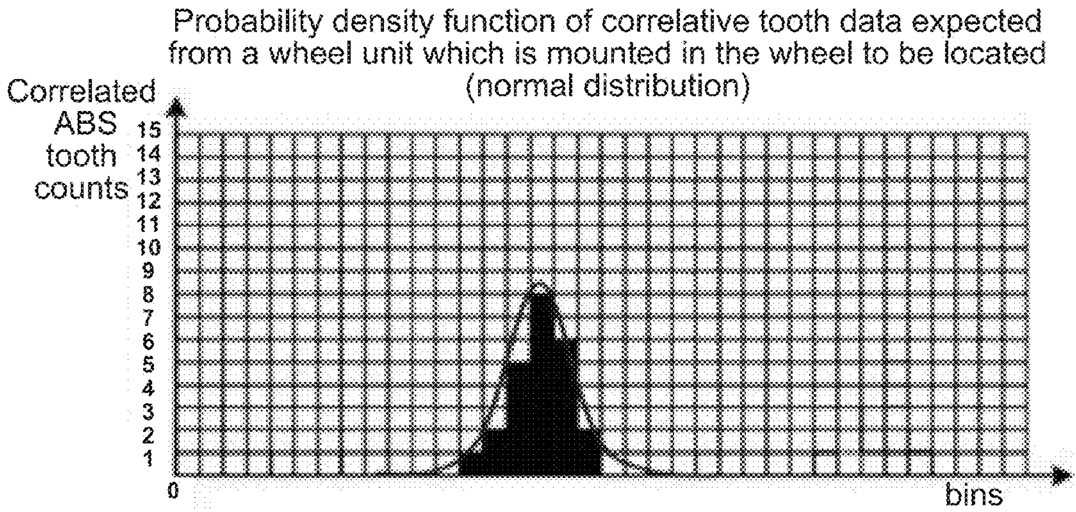



Figure 14A

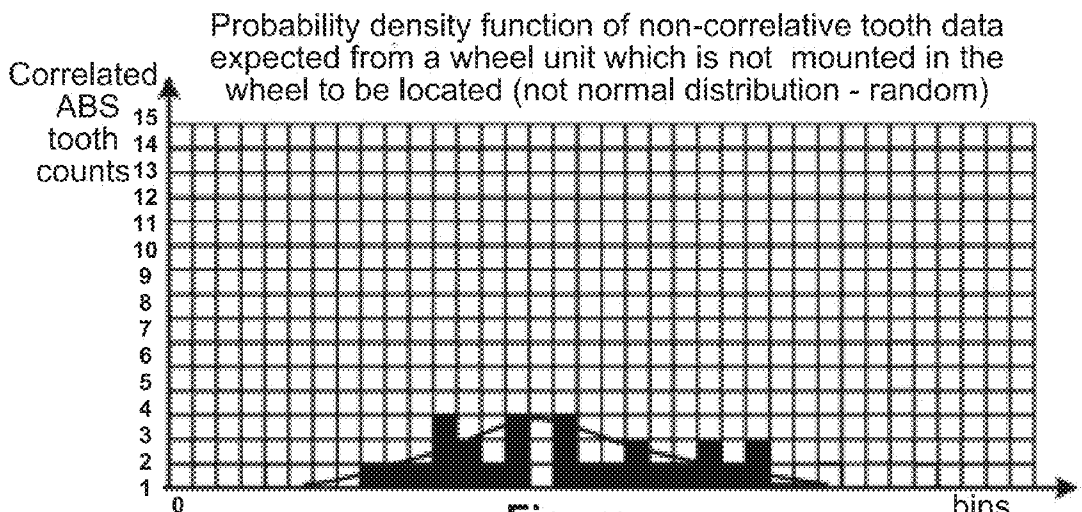



Figure 14B

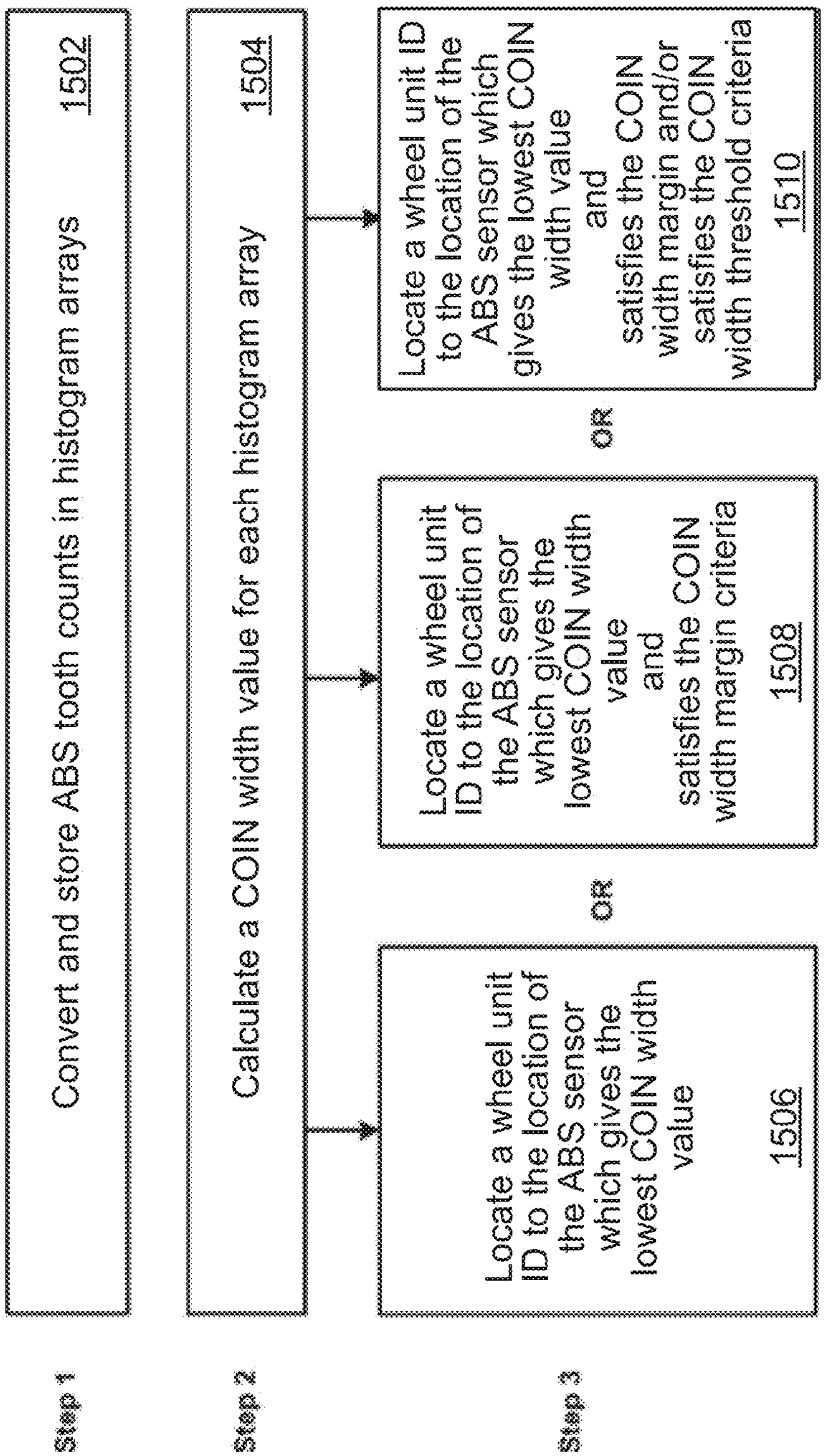

Step 1
Convert and store ABS tooth counts in histogram arrays
1502
Step 2
Calculate a COIN width value for each histogram array
1504
Step 3
Locate a wheel unit ID to the location of the ABS sensor which gives the lowest COIN width value
1506
OR
Locate a wheel unit ID to the location of the ABS sensor which gives the lowest COIN width value and satisfies the COIN width margin criteria
1508
OR
Locate a wheel unit ID to the location of the ABS sensor which gives the lowest COIN width value and satisfies the COIN width margin and/or satisfies the COIN width threshold criteria
1510

Figure 15

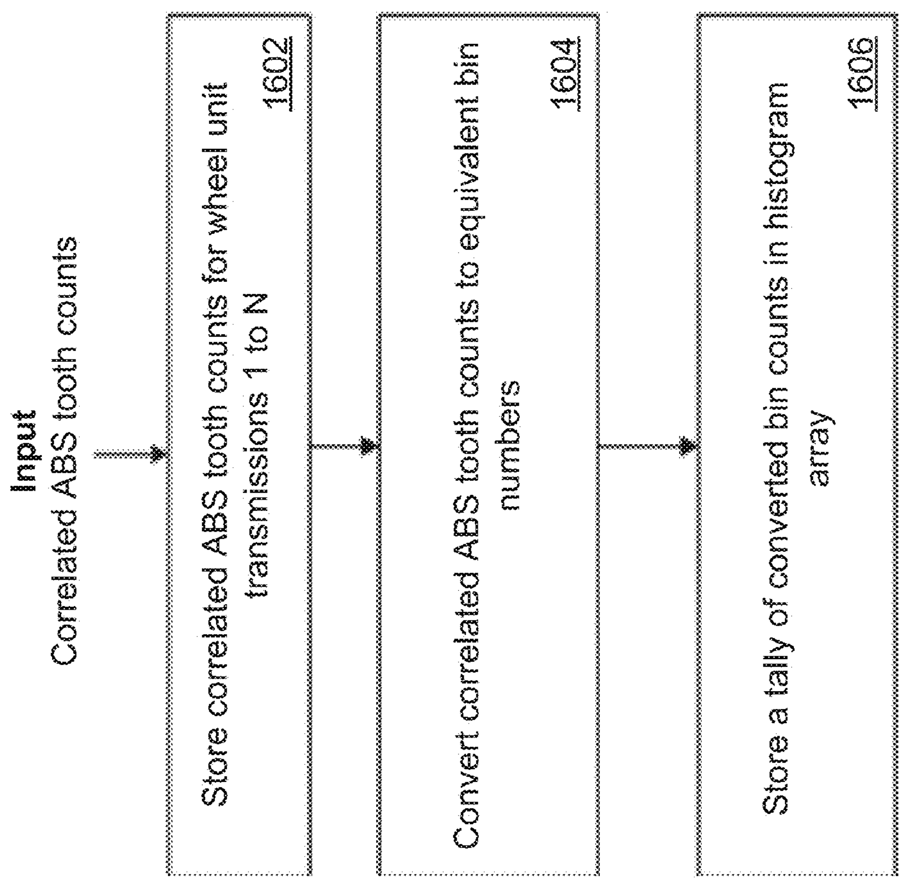

Input
Correlated ABS tooth counts
Store correlated ABS tooth counts for wheel unit transmissions 1 to N
1602
Convert correlated ABS tooth counts to equivalent bin numbers
1604
Store a tally of converted bin counts in histogram array
1606

Figure 16A

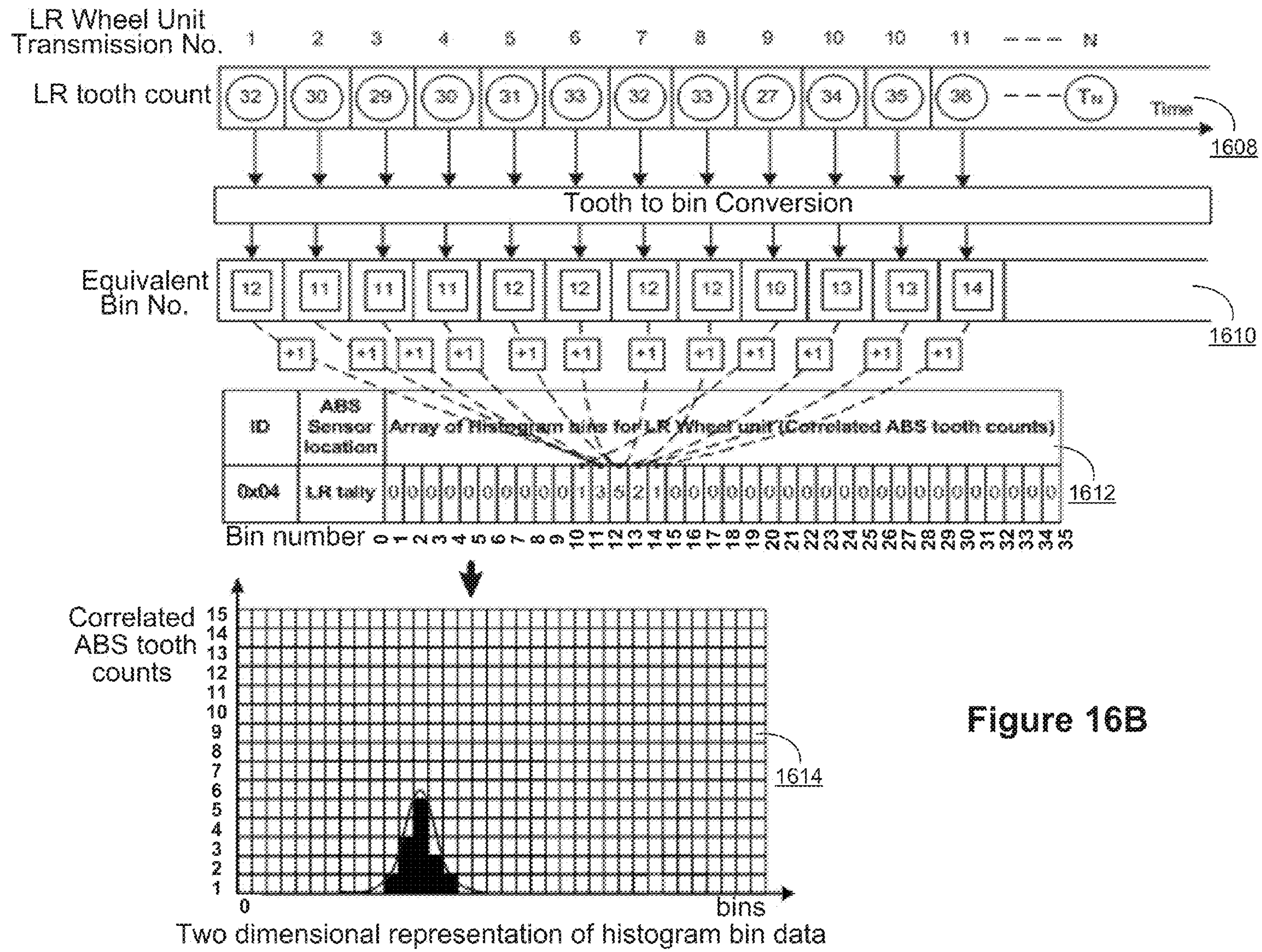

LR Wheel Unit Transmission No.
1 2 3 4 5 6 7 8 9 10 10 11 N
LR tooth count
32 30 29 30 31 33 32 33 27 34 35 36 $T_N$
Time
1608
Tooth to bin Conversion
Equivalent Bin No.
12 11 11 11 12 12 12 12 10 13 13 14
1610
+1
ID
ABS Sensor location
Array of Histogram bins for LR Wheel unit (Correlated ABS tooth counts)
0x04
LR tally
1612
Bin number
Correlated ABS tooth counts
bins
1614
Two dimensional representation of histogram bin data

Figure 16B

| WU | ABS sensor | ABS Sensor location | Histogram array for LR Wheel unit (Correlated ABS tooth counts) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | 201 | LF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | LR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 102 | 202 | LF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | LR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 103 | 203 | LF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | LR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 104 | 204 | LF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | RR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | LR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |

Figure 17

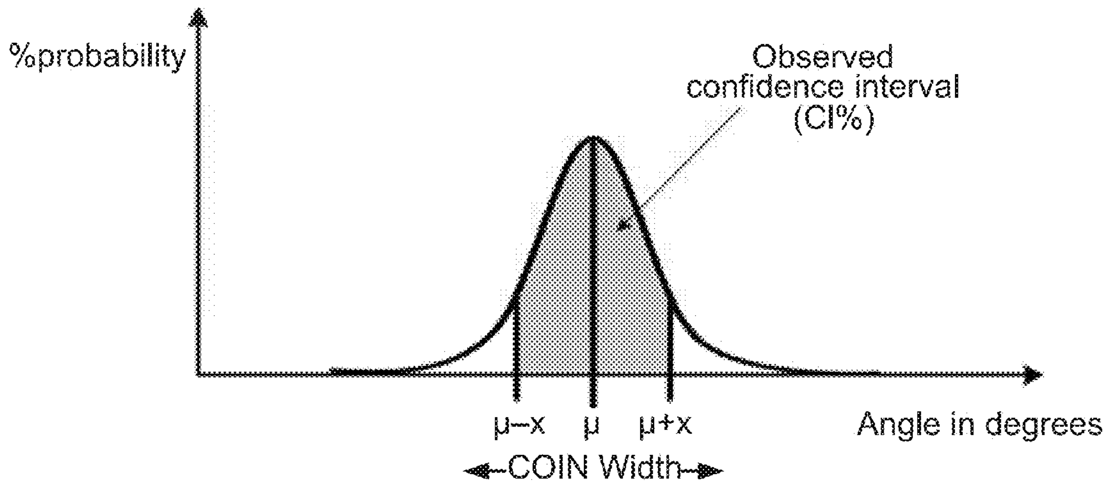



**Figure 18A**

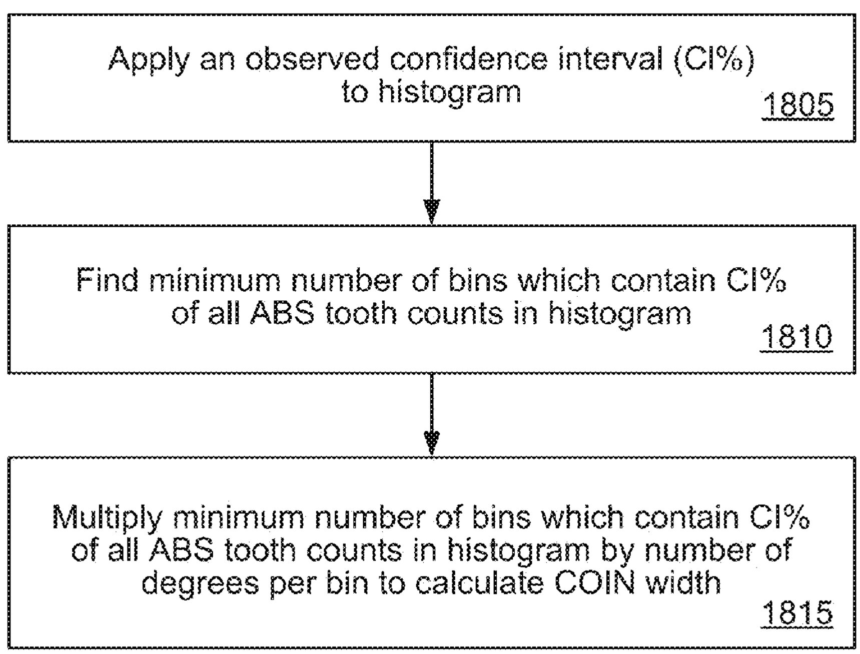



**Figure 18B**

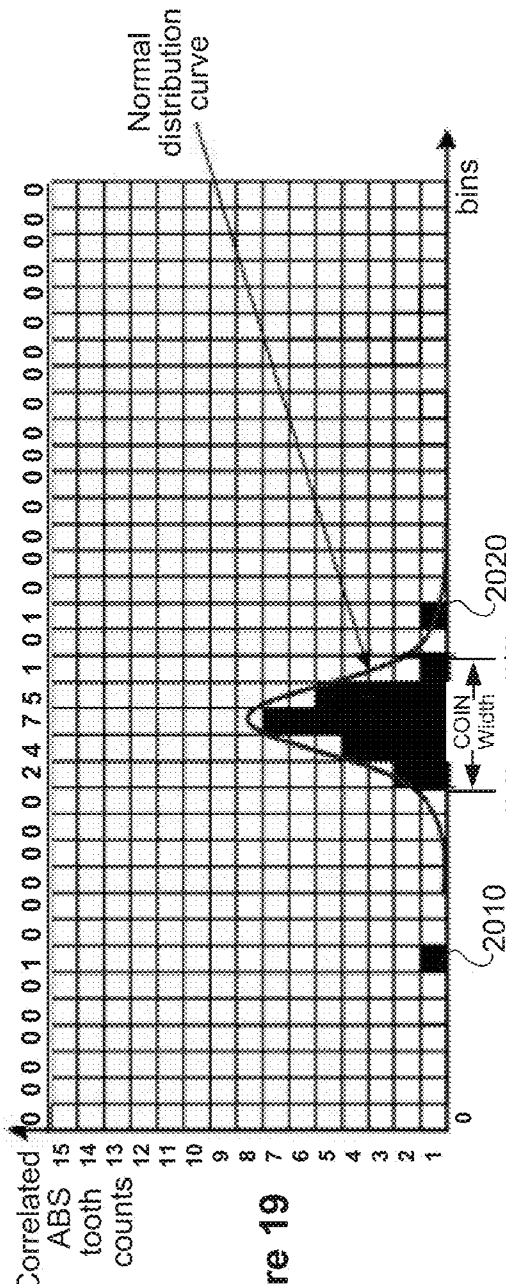



Figure 19

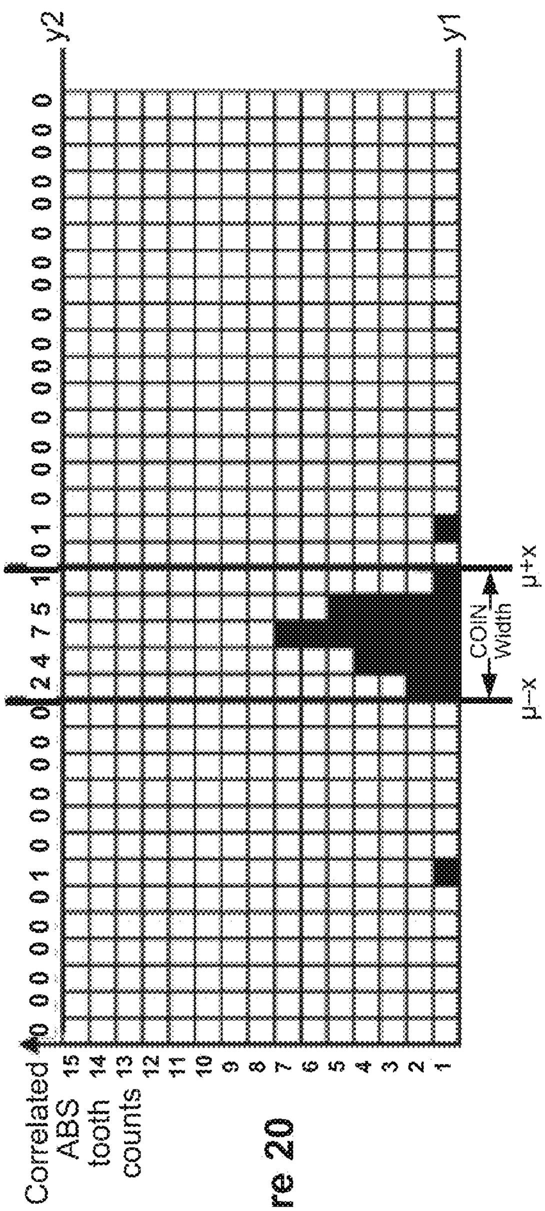



Figure 20

Histograms for wheel unit 101 mounted at location LF after transmissions

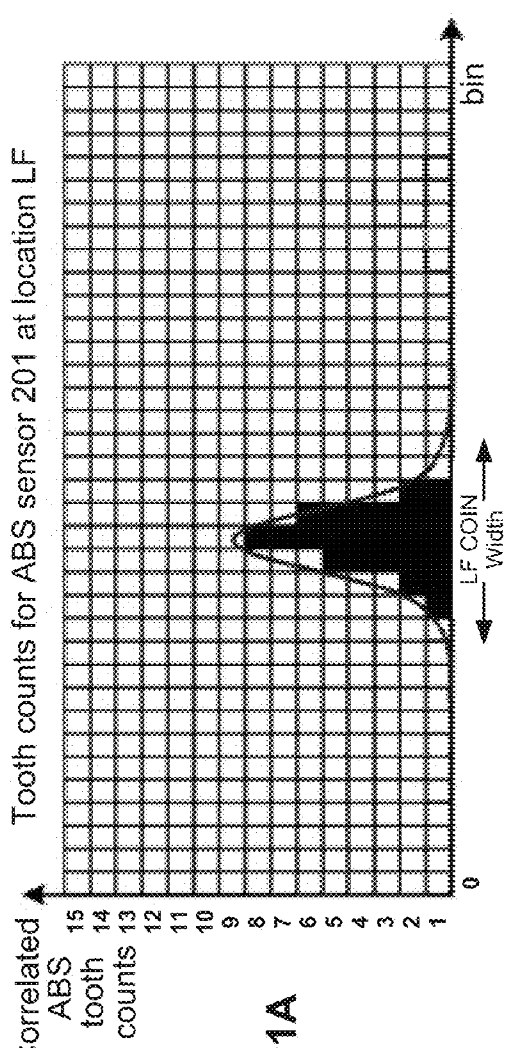



Figure 21A

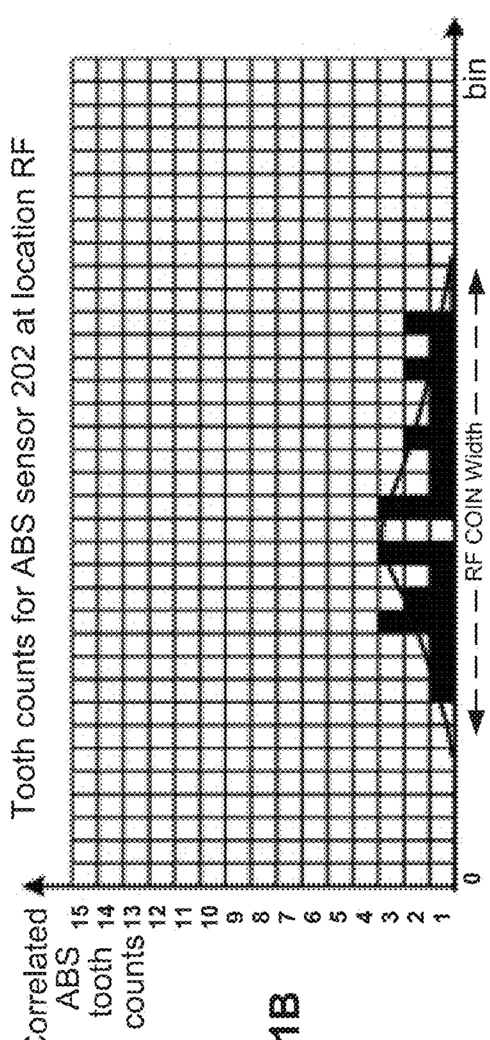



Figure 21B

Histograms for wheel unit 101 mounted at location LF after transmissions

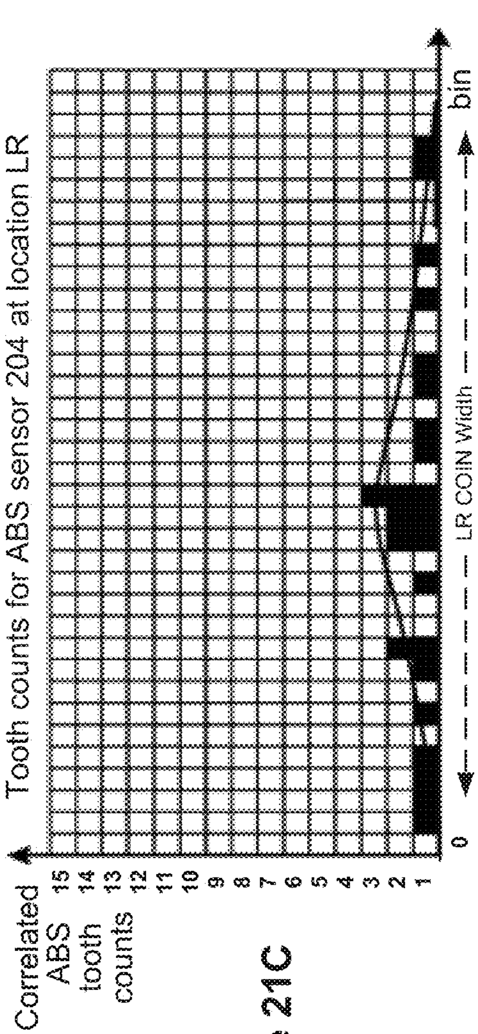



Figure 21C

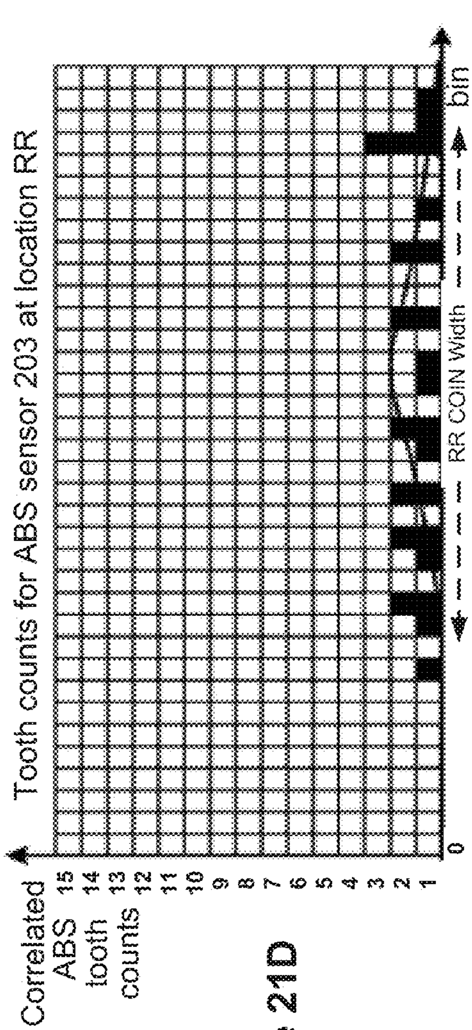



Figure 21D

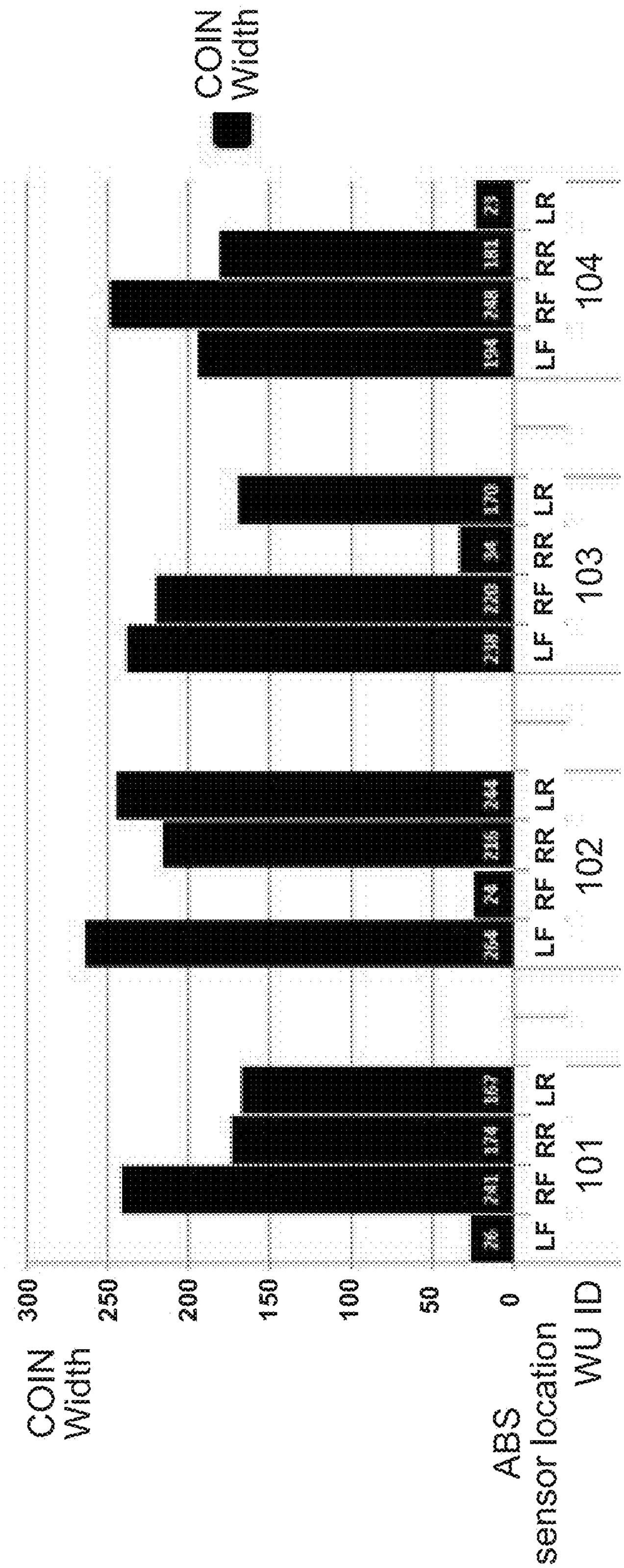
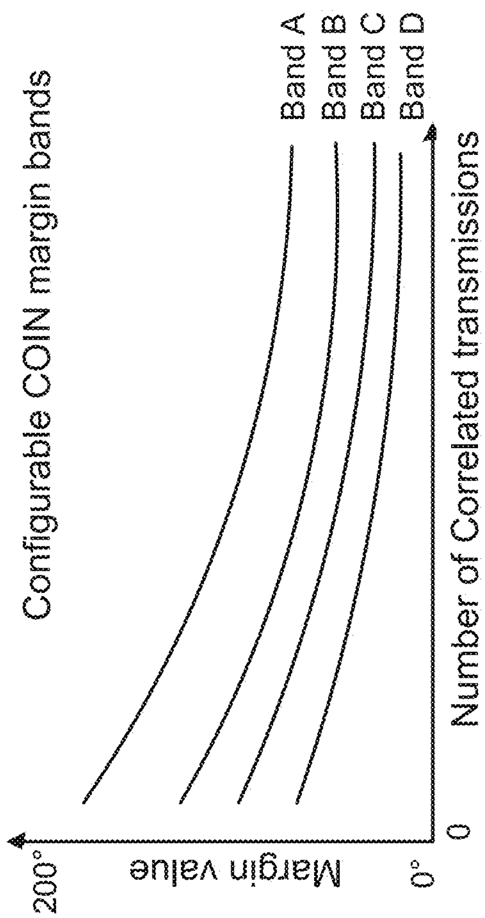

COIN Width
COIN Width
300
250
200
150
100
50
0
ABS sensor location
WU ID
LF RF RR LR
101
LF RF RR LR
102
LF RF RR LR
103
LF RF RR LR
104

Figure 22



Configurable COIN margin bands
200°
Margin value
0°
0
Number of Correlated transmissions
Band A
Band B
Band C
Band D


Figure 23

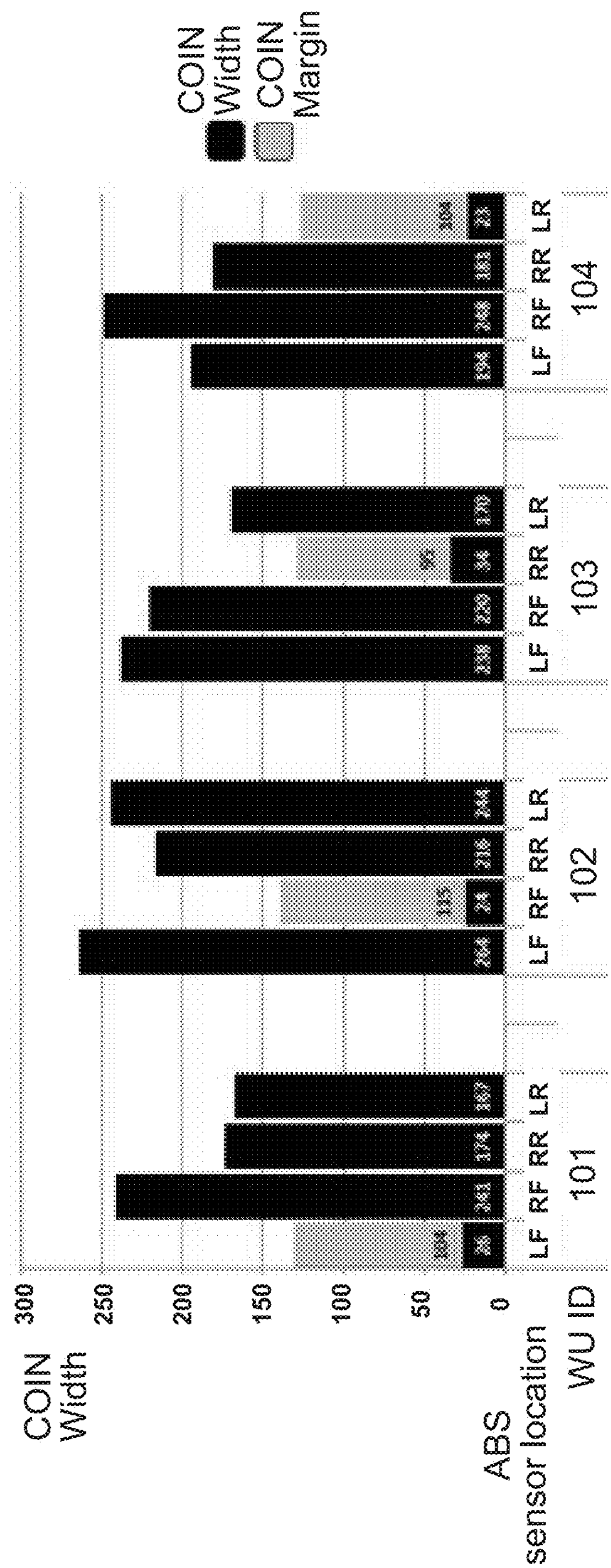

COIN Width
COIN Margin
COIN Width
300
250
200
150
100
50
0
ABS sensor location
WU ID
LF RF RR LR
101
LF RF RR LR
102
LF RF RR LR
103
LF RF RR LR
104

Figure 24

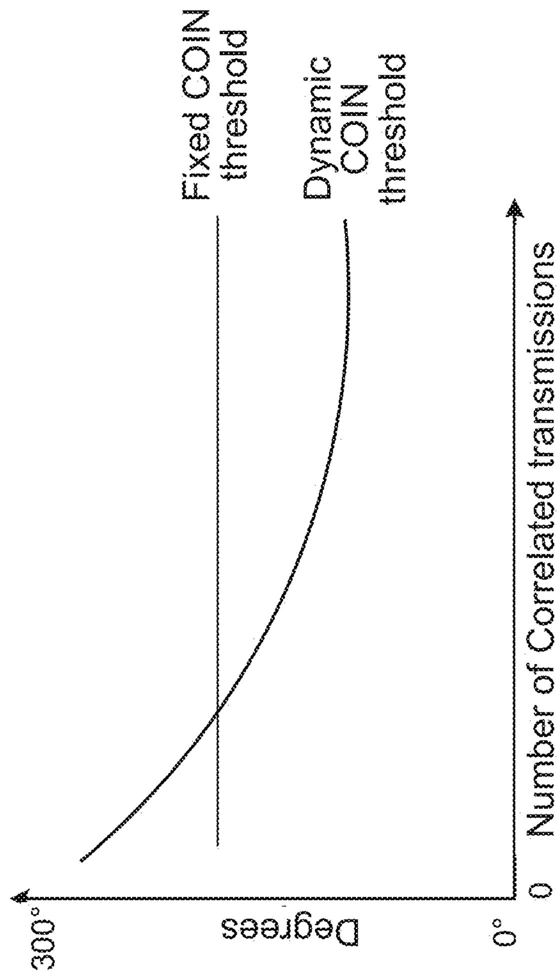

Fixed COIN threshold
Dynamic COIN threshold
300°
Degrees
0°
0
Number of Correlated transmissions

Figure 25

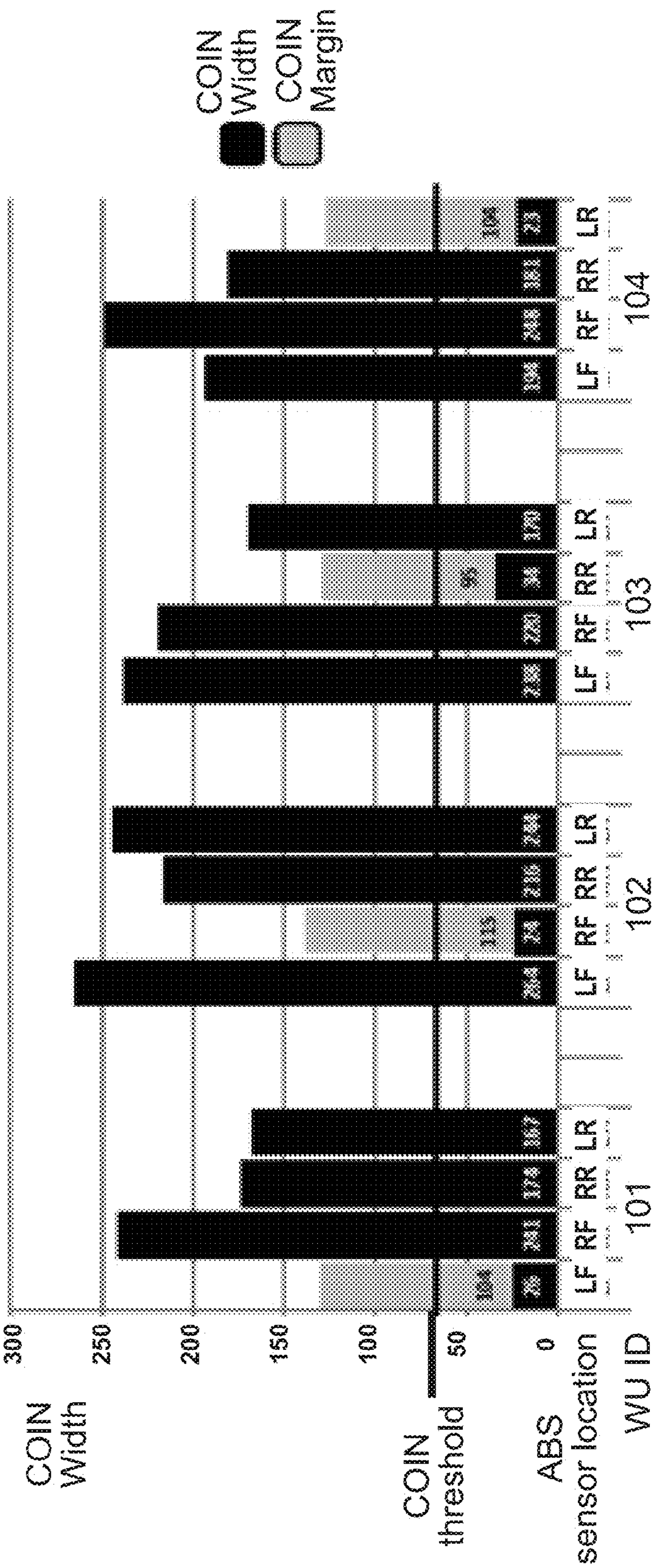

COIN Width
COIN Margin
COIN Width
COIN threshold
ABS sensor location
WU ID
300
250
200
150
100
50
0
LF
RF
RR
LR
101
102
103
104

Figure 26

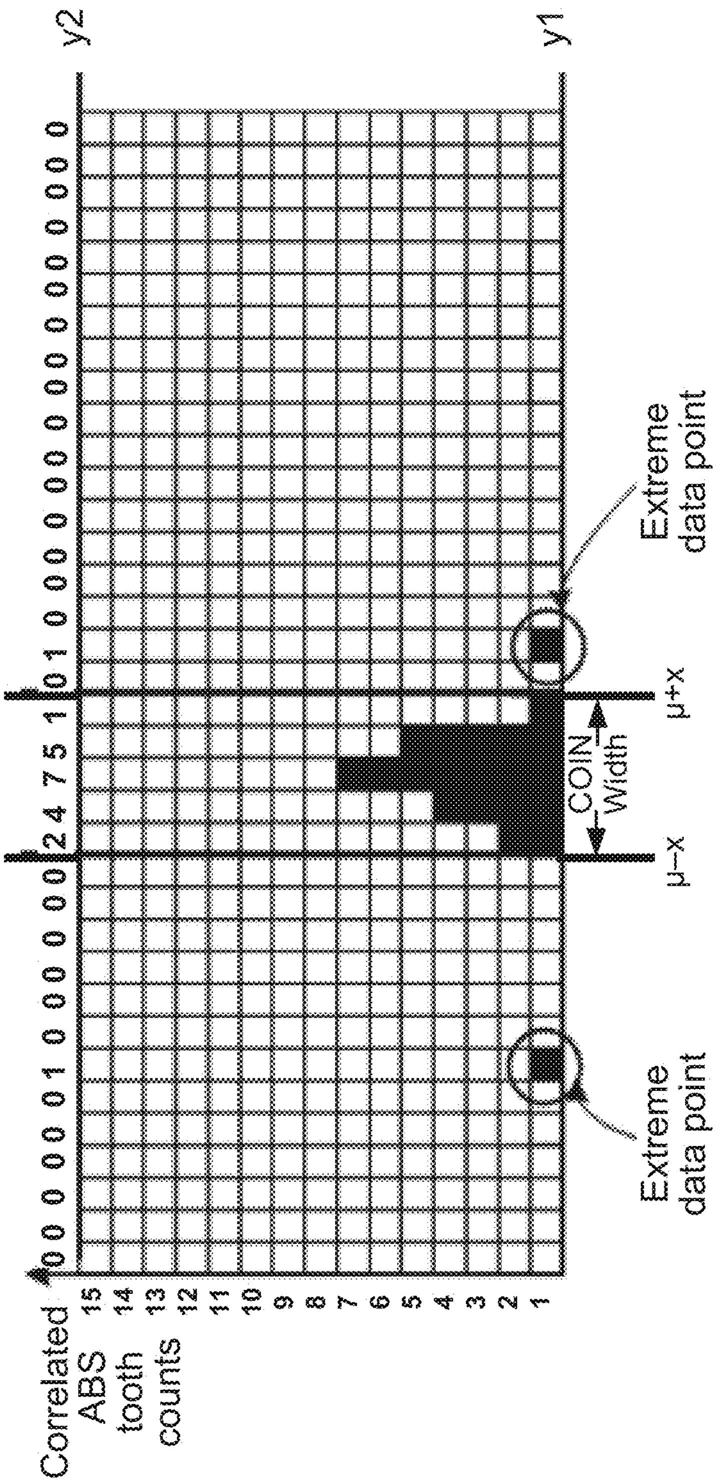

y2
y1
Correlated ABS tooth counts
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Extreme data point
Extreme data point
μ−x
μ+x
COIN Width

Figure 27

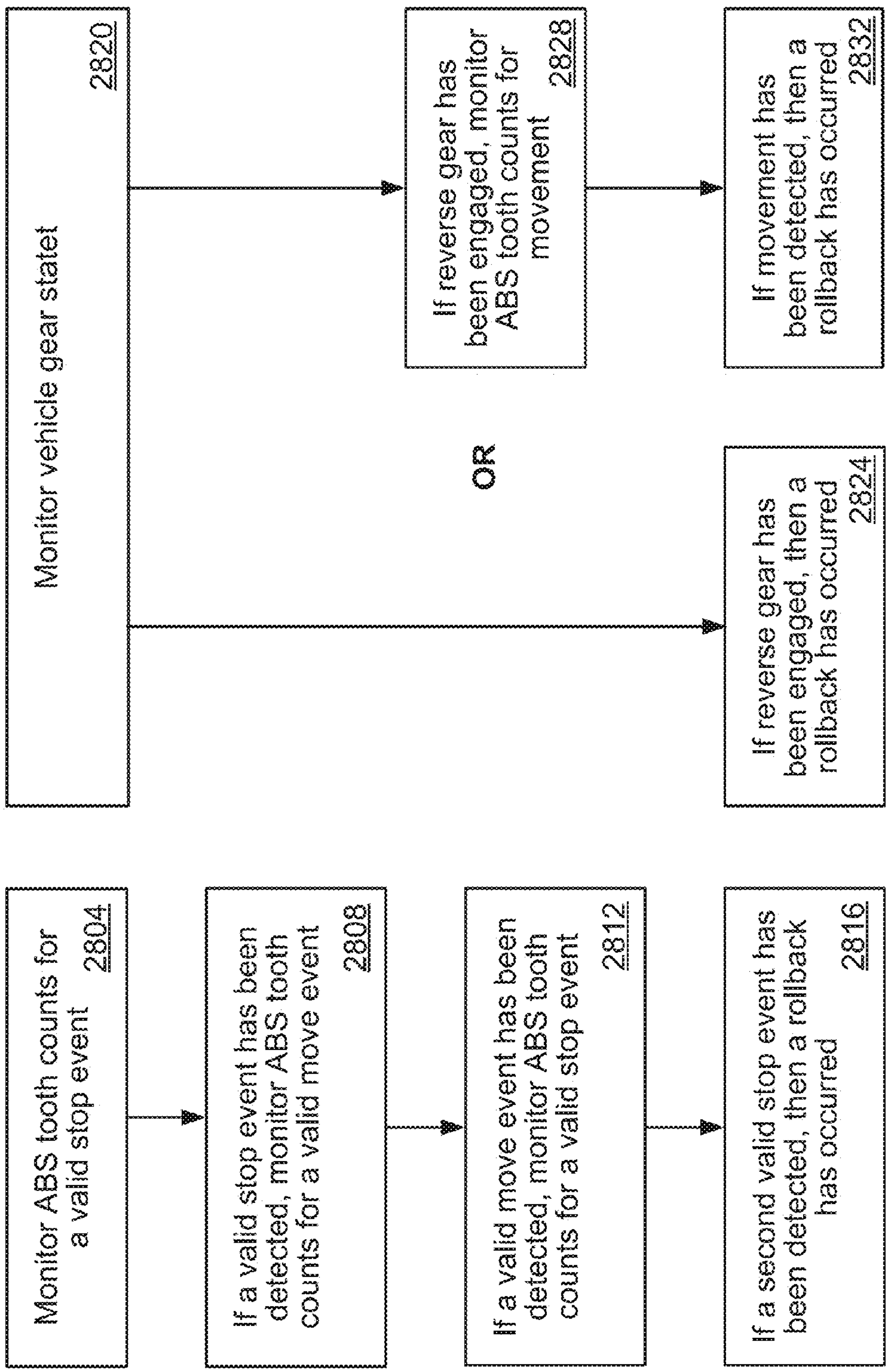



Figure 28A

Figure 28B

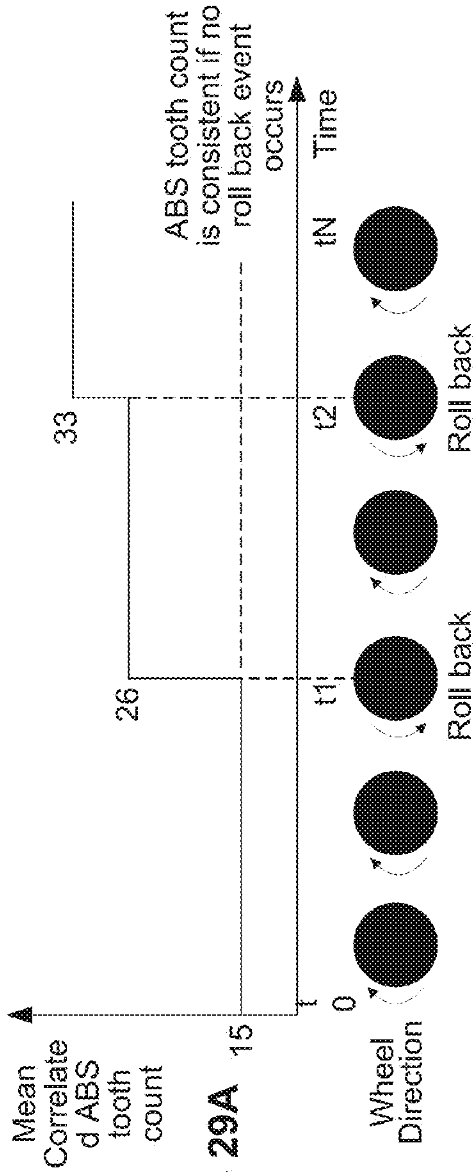



Figure 29A

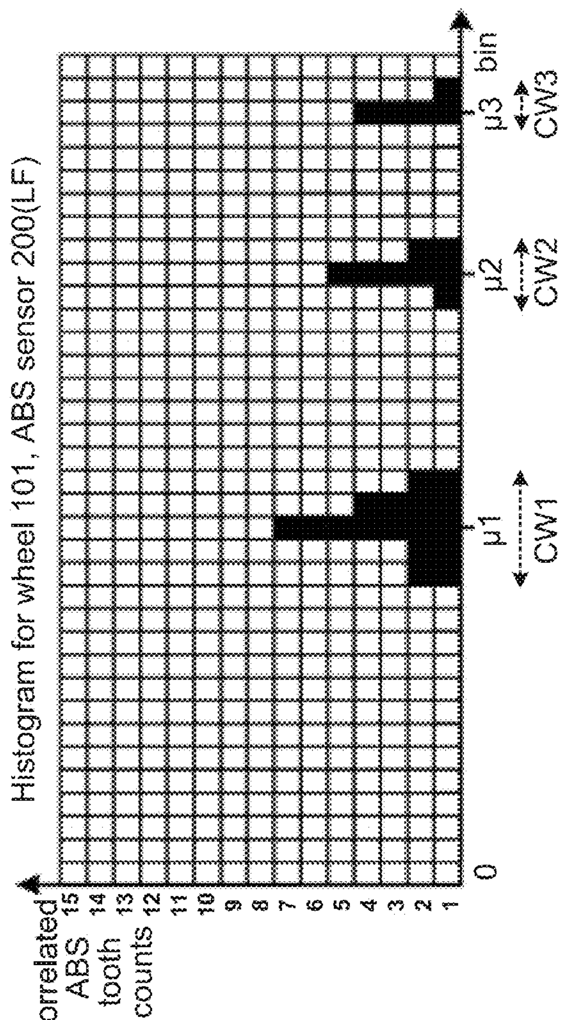



Figure 29B

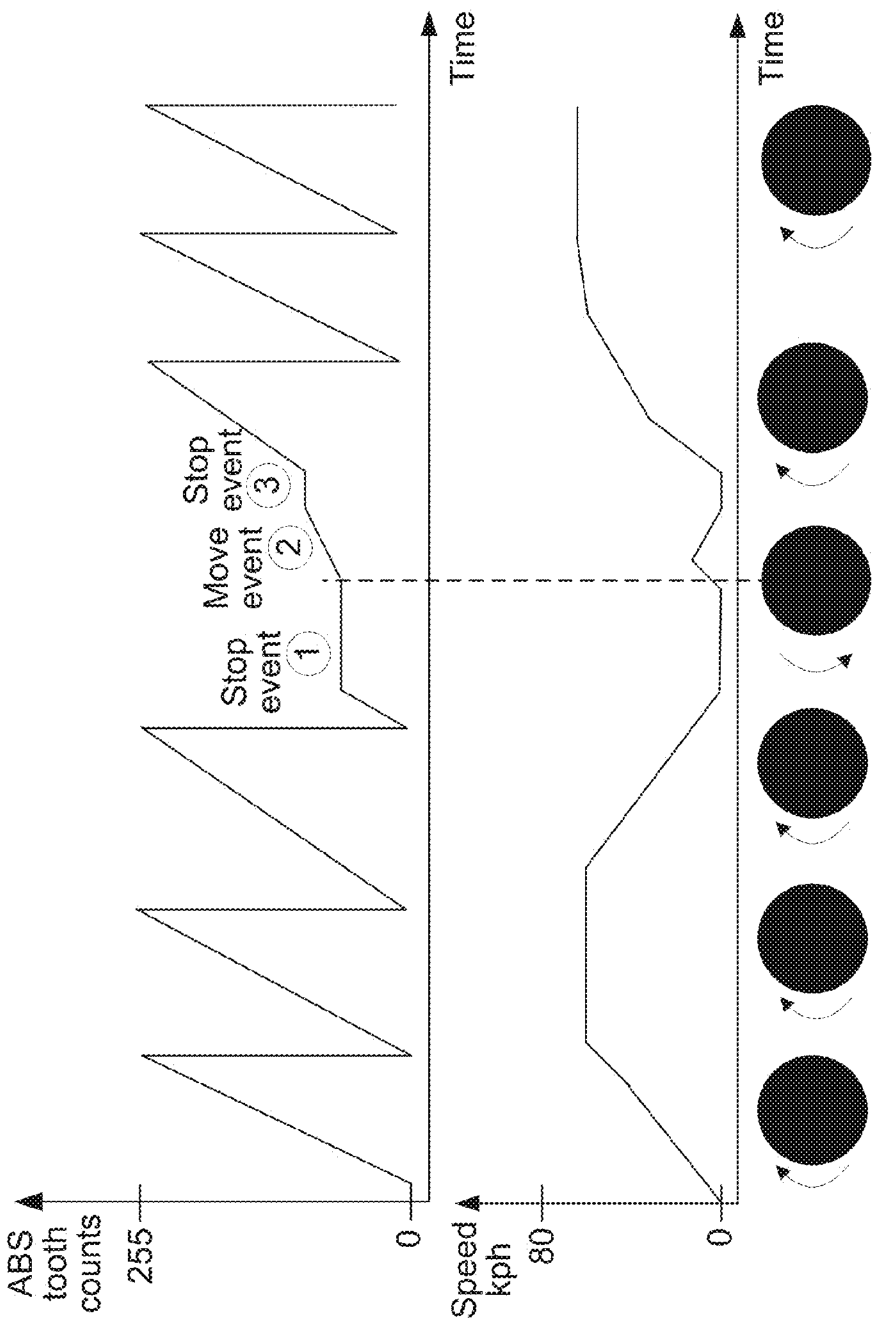

ABS tooth counts
255
0
Time
Stop event 1
Move event 2
Stop event 3
Speed kph
80
0
Time

Figure 30

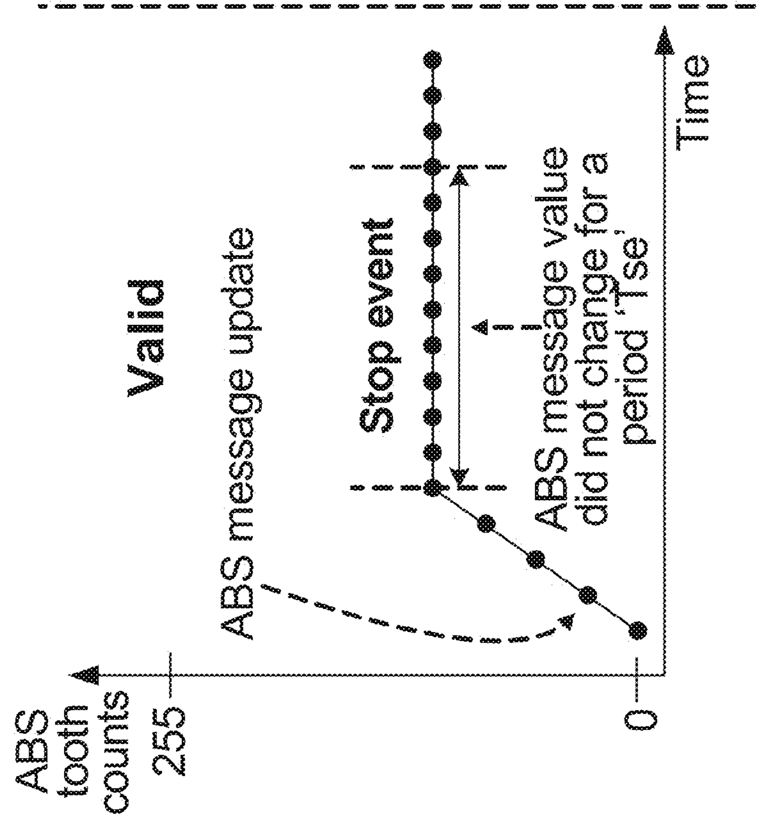



Figure 31A

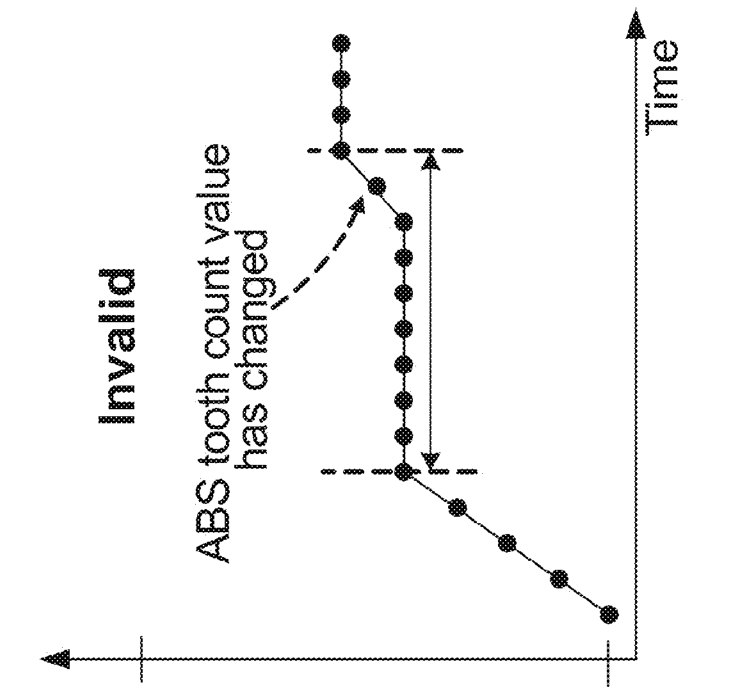



Figure 31B

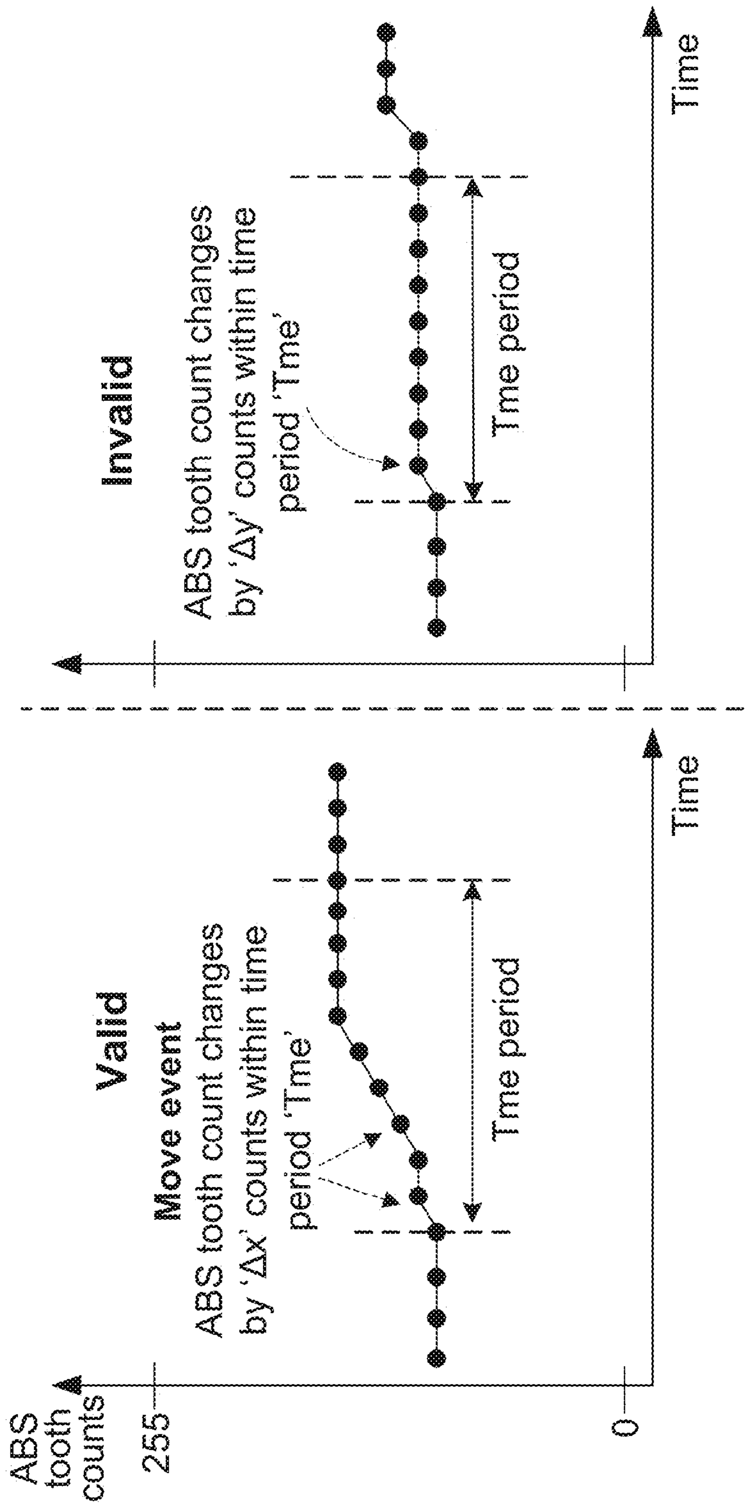
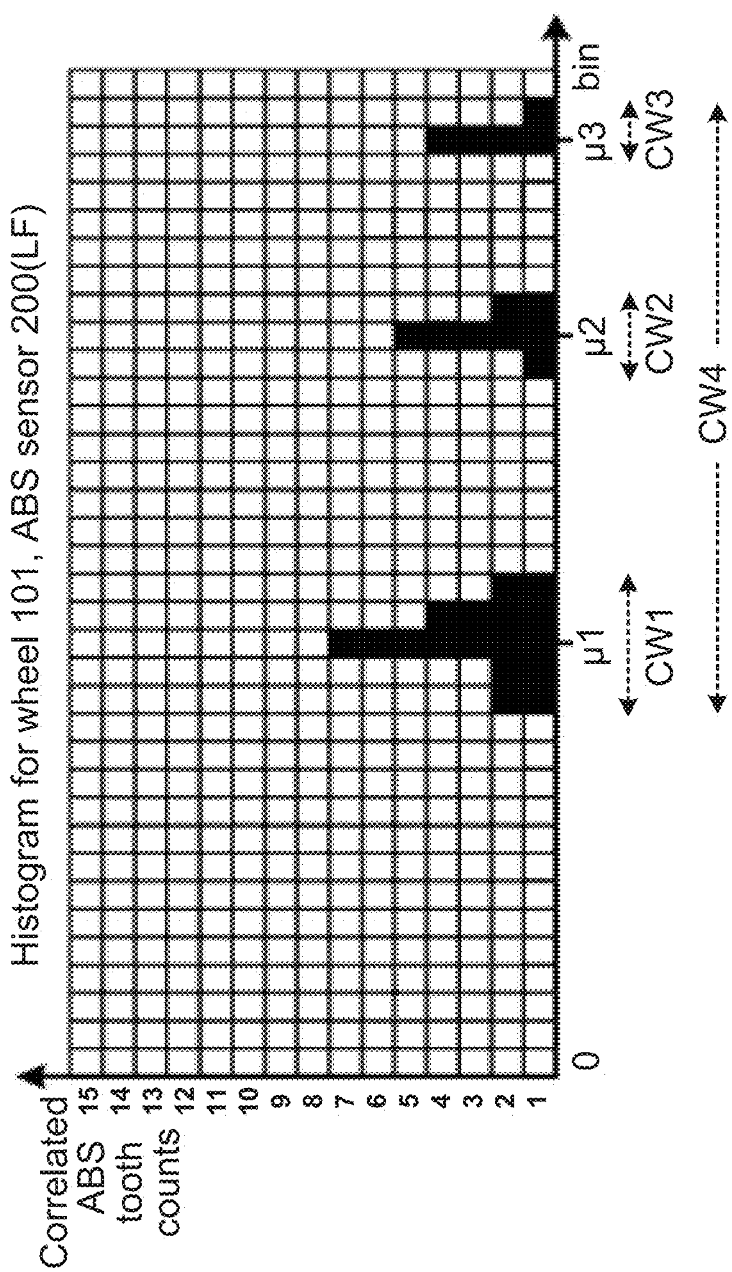



Figure 32A

Figure 32B



Histogram for wheel 101, ABS sensor 200(LF)
Correlated ABS tooth counts
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
bin
μ1
μ2
μ3
CW1
CW2
CW3
CW4


Figure 33

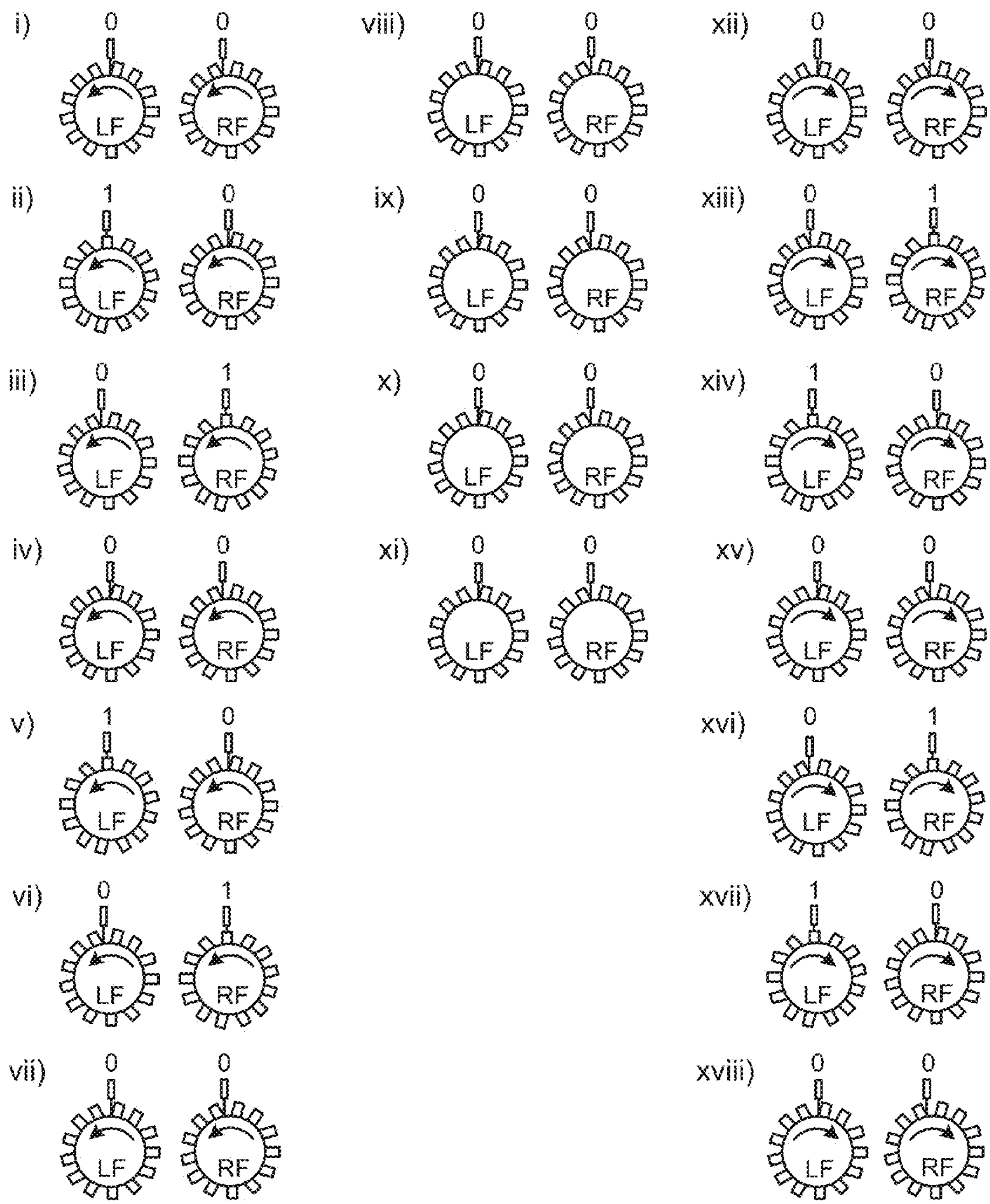

i) 0 0 LF RF
ii) 1 0 LF RF
iii) 0 1 LF RF
iv) 0 0 LF RF
v) 1 0 LF RF
vi) 0 1 LF RF
vii) 0 0 LF RF
viii) 0 0 LF RF
ix) 0 0 LF RF
x) 0 0 LF RF
xi) 0 0 LF RF
xii) 0 0 LF RF
xiii) 0 1 LF RF
xiv) 1 0 LF RF
xv) 0 0 LF RF
xvi) 0 1 LF RF
xvii) 1 0 LF RF
xviii) 0 0 LF RF

Figure 34A

| | | Change in Tooth Count | |
|---|---|---|---|
| | | LF | RF |
| i) | Direction A | 0 | 0 |
| ii) | | 1 | 0 |
| iii) | | 0 | 1 |
| iv) | | 0 | 0 |
| v) | | 1 | 0 |
| vi) | | 0 | 1 |
| vii) | | 0 | 0 |
| viii) | Stationary | 0 | 0 |
| ix) | | 0 | 0 |
| x) | | 0 | 0 |
| xi) | | 0 | 0 |
| xii) | Direction B | 0 | 0 |
| xiii) | | 0 | 1 |
| xiv) | | 1 | 0 |
| xv) | | 0 | 0 |
| xvi) | | 0 | 1 |
| xvii) | | 1 | 0 |
| xviii) | | 0 | 0 |

Figure 34B

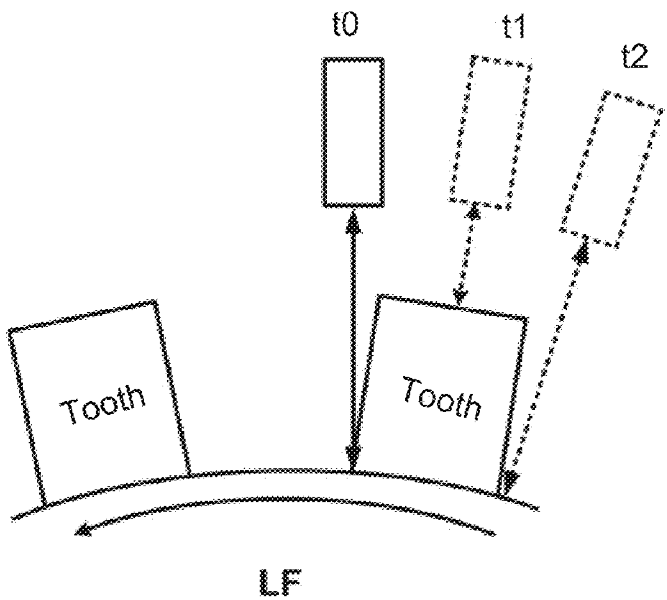



Figure 35A

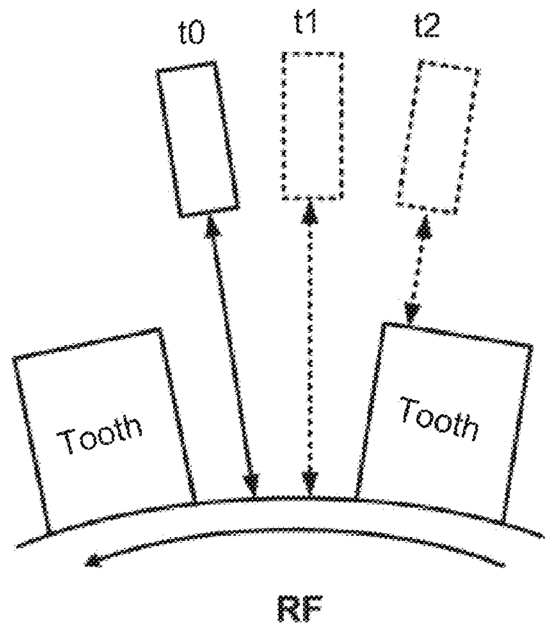



Figure 35B

| | Change in tooth count | |
|---|---|---|
| | LF | RF |
| t0 | 0 | 0 |
| t1 | 1 | 0 |
| t2 | 0 | 1 |

Figure 35C

Time t0 is an enlargement of Figs. 34A and 34B, Section vii

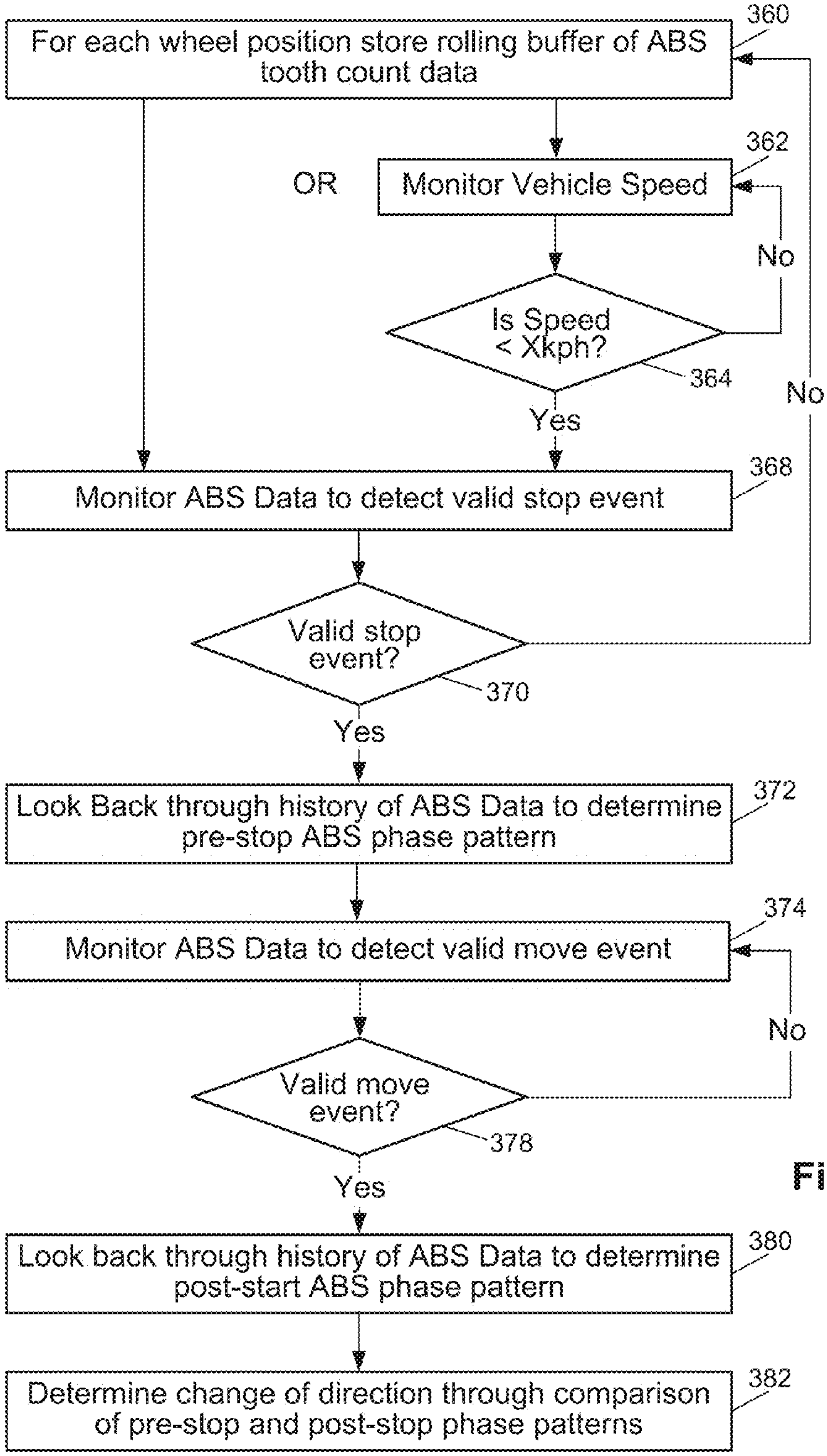

For each wheel position store rolling buffer of ABS tooth count data
360
OR
Monitor Vehicle Speed
362
No
Is Speed < Xkph?
364
No
Yes
Monitor ABS Data to detect valid stop event
368
Valid stop event?
370
Yes
Look Back through history of ABS Data to determine pre-stop ABS phase pattern
372
Monitor ABS Data to detect valid move event
374
No
Valid move event?
378
Yes
Look back through history of ABS Data to determine post-start ABS phase pattern
380
Determine change of direction through comparison of pre-stop and post-stop phase patterns
382

Figure 36

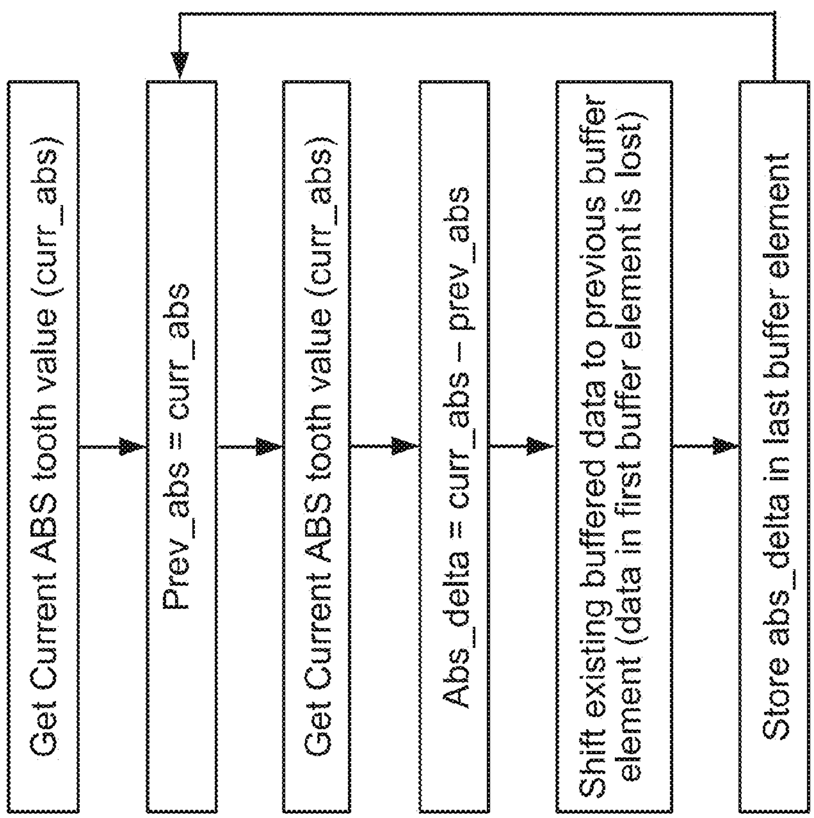

Get Current ABS tooth value (curr_abs)
Prev_abs = curr_abs
Get Current ABS tooth value (curr_abs)
Abs_delta = curr_abs – prev_abs
Shift existing buffered data to previous buffer element (data in first buffer element is lost)
Store abs_delta in last buffer element

Figure 37A

| Element | 0 | | x-5 | x-4 | x-3 | x-2 | x-1 |
|---|---|---|---|---|---|---|---|
| LF | $z^{-(x-1)}$ | ... | $z^{-4}$ | $z^{-3}$ | $z^{-2}$ | $z^{-1}$ | $z^{0}$ |
| RF | $z^{-(x-1)}$ | ... | $z^{-4}$ | $z^{-3}$ | $z^{-2}$ | $z^{-1}$ | $z^{0}$ |
| RR | $z^{-(x-1)}$ | ... | $z^{-4}$ | $z^{-3}$ | $z^{-2}$ | $z^{-1}$ | $z^{0}$ |
| LR | $z^{-(x-1)}$ | ... | $z^{-4}$ | $z^{-3}$ | $z^{-2}$ | $z^{-1}$ | $z^{0}$ |

ABS data buffer of 'x' elements

Figure 37B

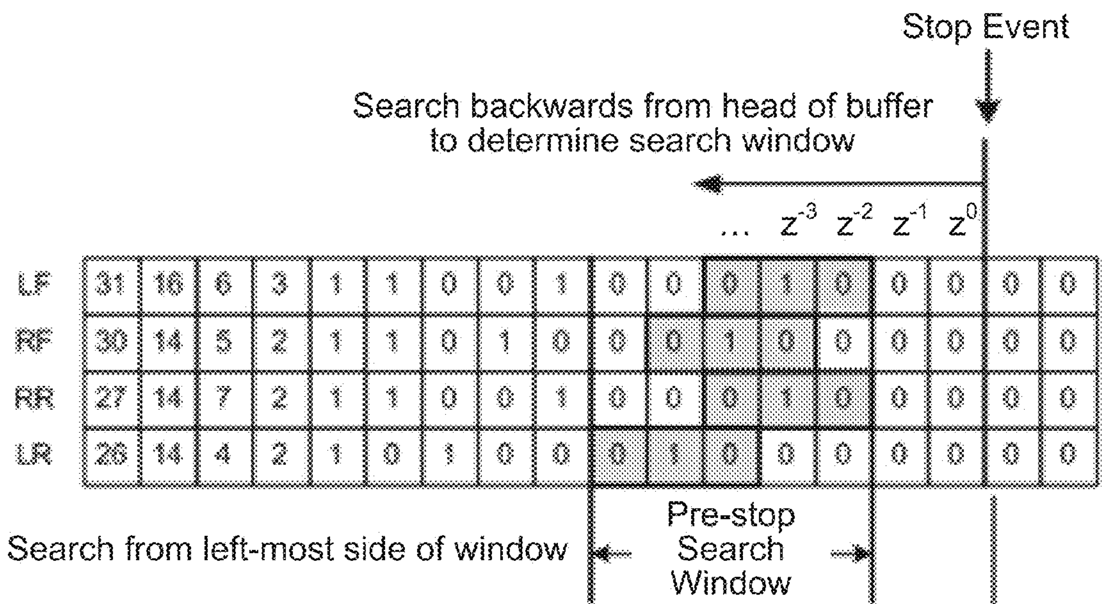



Figure 38A

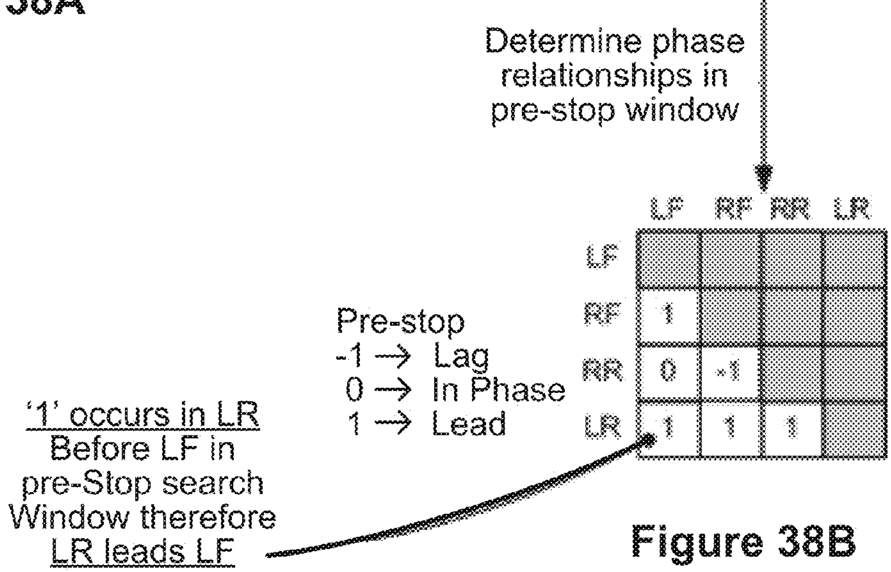



Figure 38B

Upper Triangle:
Post-start phase

| | LF | RF | RR | LR |
|---|---|---|---|---|
| LF | | RF vs LF | RR vs LF | LR vs LF |
| RF | RF vs LF | | RR vs RF | LR vs RF |
| RR | RR vs LF | RR vs RF | | LR vs RR |
| LR | LR vs LF | LR vs RF | LR vs RR | |

Lower Triangle
Pre-stop phase

**Decision Matrix**

**Figure 38C**

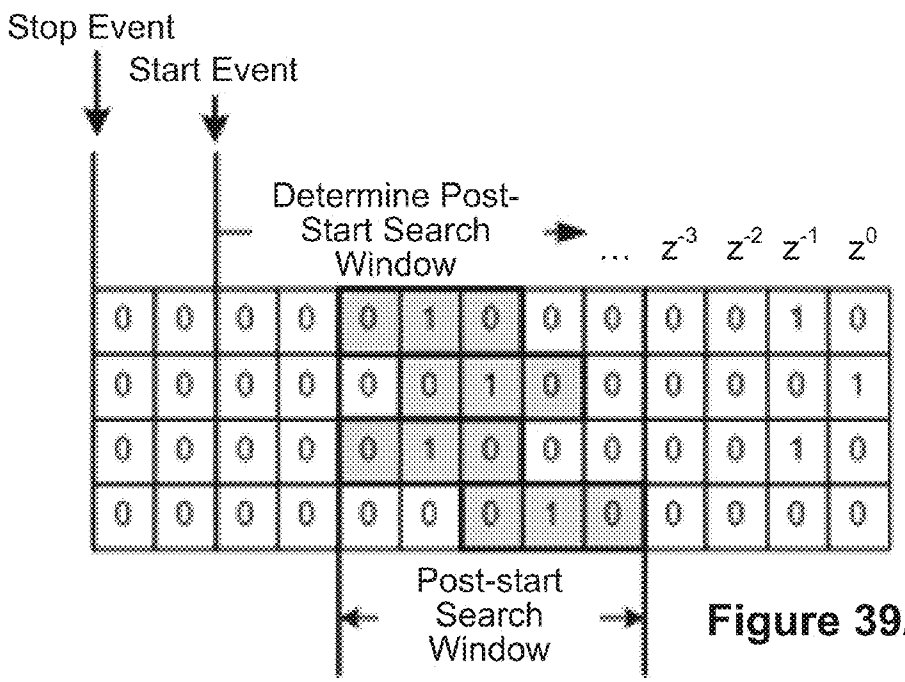



Figure 39A

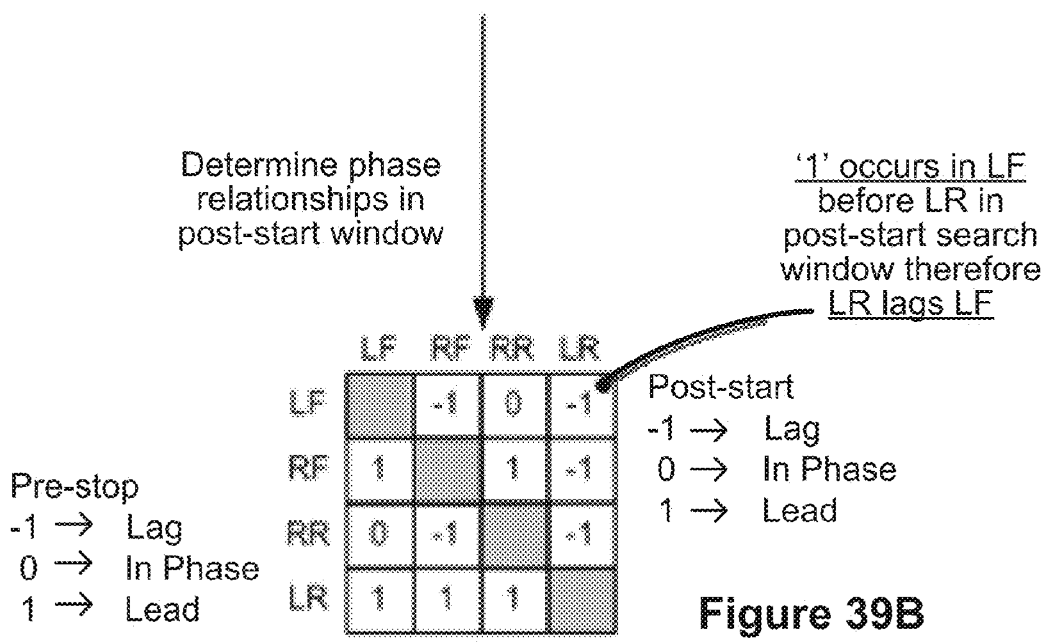



Figure 39B

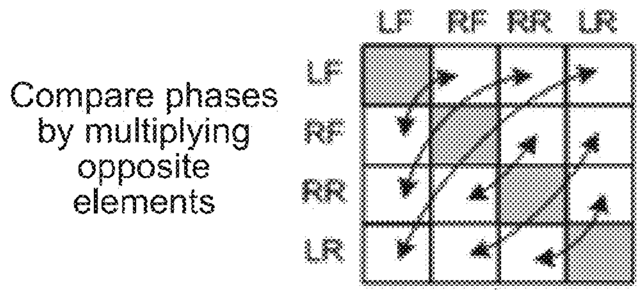



Figure 40A

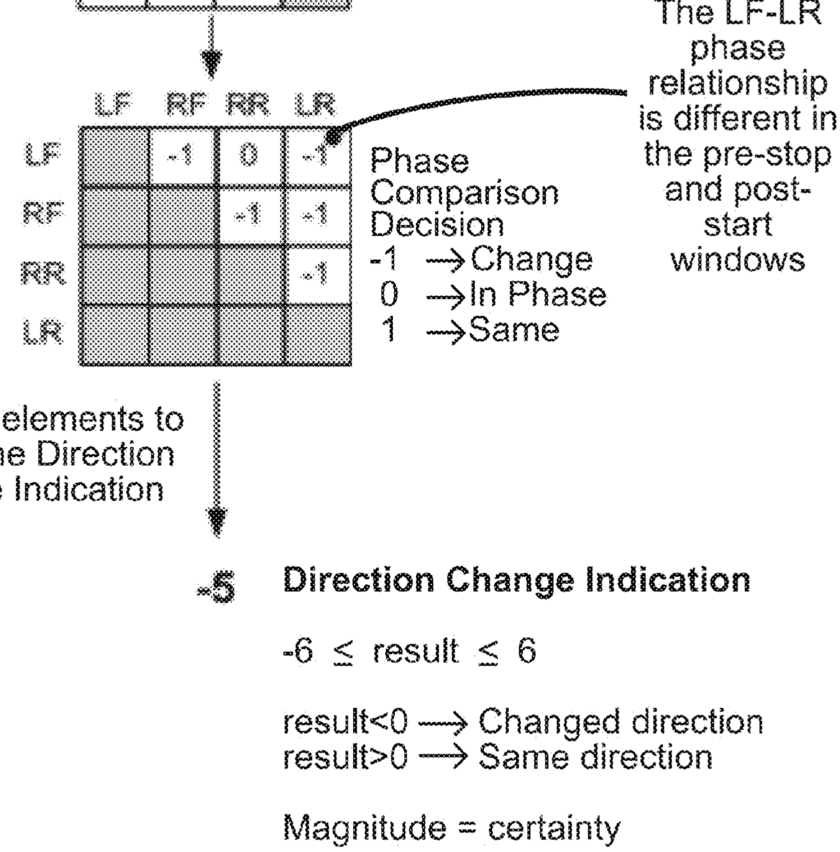



Figure 40B

# SYSTEM AND METHOD FOR PERFORMING AUTO-LOCATION OF A TIRE PRESSURE MONITORING SENSOR ARRANGED WITH A VEHICLE WHEEL USING CONFIDENCE INTERVAL ANALYSIS AND CHANGE OF WHEEL DIRECTION

## PRIORITY

This application is a continuation-in-part of U.S. application Ser. No. 13/973,855 filed Aug. 22, 2013, entitled "System and method for performing auto-location of a tire pressure monitoring sensor arranged with a vehicle wheel using confidence interval analysis and rollback events," disclosure of which is incorporated here in its entirety.

## BACKGROUND

1. Technical Field

This application relates generally to a system and method for performing auto-location of a wheel in a vehicle and more particularly to a tire pressure monitoring system and method for performing auto-location of a tire pressure monitoring sensor arranged with a vehicle wheel using confidence interval analysis. This application further relates to a tire pressure monitoring system and method for performing auto-location of a tire pressure monitoring sensor using confidence interval analysis which takes into consideration change of wheel direction.

2. Related Art

In tire pressure monitoring systems, performing auto-location of a wheel is needed for a number of reasons. Tire pressure monitoring systems generally include a tire pressure monitoring (TPM) sensor in or at each wheel of a vehicle and a central controller which receives tire pressure information from each TPM sensor, to be reported to the driver of the vehicle. Auto-location is the identification of each TPM sensor and determination of its position on the vehicle, automatically and without human intervention. Auto-location may be done initially upon installation and subsequently in the event of tire rotation or replacement. Performing auto-location involves determining the identity or serial number of a TPM sensor in each of the wheels in the car. In premium vehicles, knowing the identity of the TPM sensor in each wheel allows a pressure by position display to be implemented and shown to the driver. In basic vehicles with different placard tire pressures for front and rear axles, it is desirable to know TPM sensor identities and positions in order to check pressure against a correct threshold for an applicable axle.

Auto-location may use antilock brake systems ("ABS") which are employed in most vehicles. The ABS allows independent wheel speeds to be monitored in near real-time. In one embodiment, the wheel phase and/or speed data includes or is based on the ABS data. The ABS data typically indicates ABS tooth counts. By analyzing ABS tooth counts, correlation between ABS data and other data from TPM sensors can be used to locate wheel positions where the TPM sensors are arranged. ABS sensors provide the ABS data and may be associated with one or more wheels. As one example, ABS sensors are associated with each wheel of a vehicle, or with selected wheels of the vehicle. The wheel phase and/or speed data is not limited to the ABS data. A sensor, a device, a system, or a mechanism that may provide wheel phase and/or speed data directly or in various forms may be used in addition to, or instead of antilock brake systems.

The ABS data may be analyzed statistically. For instance, a historic trace of the ABS data may be observed to determine the location of a wheel based on a statistically significant value of the ABS data, or based on a lowest standard variation of ABS tooth count values. Statistical analysis involving a standard deviation, a variance, dispersion, etc. may fully take even extreme data points into consideration and such data points may significantly influence determination of the location of the wheel. The extreme data points may be caused by nuisance factors such as road noise, vehicle vibrations, error in ABS source data, communication delays, etc. Accordingly, the extreme data points may cause irregular and unexpected changes to the ABS data which may bias the auto-location of the wheel.

The ABS data such as ABS tooth counts increment upwards, regardless of whether a wheel associated with an ABS sensor rotates clockwise or counter clockwise. Any counter clockwise movement over the course of a drive may cause the mean of correlated ABS tooth counts to shift. Accordingly, the counter clockwise movement of the wheel may need to be monitored and upon detection of such movement, it is desirable to take the ABS tooth counts associated with the counter clockwise movement into a consideration in performing the auto-location. Moreover, it may be desirable to consider change of wheel direction associated with a vehicle as such change of direction may affect the auto-location determination.

## SUMMARY

The present embodiments are directed to auto-location systems and methods in which ABS sensor data is correlated with a radio frequency transmission from a TPM sensor located at or on a specific wheel and such correlation is analyzed based on a confidence interval of a histogram representing correlated ABS sensor data to determine a location of the TPM sensor at or on the specific wheel on a vehicle. The present embodiments determine the wheel location in order to determine the location of a TPM sensor arranged with the wheel. In the present embodiments, the auto-location of a wheel indicates auto-location of the TPM sensor arranged with the wheel so that parameters from the TPM sensor may be assigned to the wheel. ABS sensor data, such as correlated ABS tooth counts, are converted and stored in a histogram array. A normal or Gaussian distribution pattern is portrayed from a histogram of an ABS sensor associated with a wheel having a TPM sensor which transmits RF transmissions. On the other hand, a random distribution pattern is portrayed from a histogram of an ABS sensor associated with different wheels where the TPM sensor is not arranged. The location of the wheel where the TPM sensor is mounted is identified based on the histogram of actual ABS sensor data which resembles a normal distribution pattern. The histogram having the most normal distribution pattern shows a lowest confidence interval width. The histogram having a more random distribution pattern shows a significantly higher confidence interval width. Based on the lowest confidence interval width, the wheel location of the TPM sensor is identified.

By way of example, one embodiment of a wheel auto-location method includes (i) the step of receiving a radio frequency (RF) transmission that indicates one-measurement point during a rotation of a wheel and tire pressure monitoring (TPM) sensor parameters, wherein the RF transmission is associated with a phase correlation data storage event trigger and (ii) the step of storing a current content of a rolling window of an antilock brake system (ABS) data indicative of a wheel phase angle in response to the phase correlation data storage event trigger, wherein a time period covered by the rolling window is the same or greater than a time period

between the one-measurement point and a receipt point of the RF transmission, and the current content of the rolling window corresponds to the ABS data between the one-measurement point and the receipt point of the RF transmission. The one-measurement point is calculated based on the time period between the one-measurement point and the receipt point of the RF transmission, and relevant ABS data is determined from the current content of the rolling window of the ABS data based on the one-measurement point over time. The relevant correlated ABS data is converted in a histogram array and a confidence interval (COIN) width value is calculated from the histogram array. The wheel auto-location method further includes the step of applying an auto-location algorithm to identify a specific location of the wheel based on a lowest COIN width value where the TPM sensor parameters are associated with the specific location of the wheel.

In determining the COIN width value, change of wheel direction may need to be taken into consideration. The change of wheel direction may result in a shift in the perceived mean of correlated ABS tooth counts. Accordingly, the change of wheel direction may change means of correlated ABS tooth counts which in turn may result in incorrect auto-location. Detecting and managing the change of direction ensures that the accurate location of a wheel unit can be made.

In one embodiment, a method for determining change of direction of a vehicle includes steps of maintaining a rolling window of ABS data indicative of ABS tooth count and capturing a relevant rolling window of ABS data at the predetermined one-measurement point; storing the rolling window of the ABS data indicative of ABS tooth in a buffer; monitoring the ABS data and detecting a valid stop event which causes the rate of change of ABS tooth count to substantially decrement to zero; and monitoring the ABS data and detecting a valid move event which causes the rate of change of ABS tooth count to substantially increment from zero. The method also includes steps of determining a pre-stop phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately prior to the valid stop event; determining a post-start phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately subsequent to the valid move event; and correlating the pre-stop phase relationship and the post-start phase relationship to determine change of direction and confidence level.

Another embodiment of the present invention includes a wheel auto-location method including steps of receiving an RF transmission indicating a predetermined one-measurement point during rotation of a wheel and TPM sensor parameters; calculating the predetermined one-measurement point based on the RF transmission; maintaining a rolling window of ABS data and capturing a relevant rolling window of ABS data at the predetermined one-measurement point; and monitoring the ABS data and detecting change of direction as described in the method for determining change of direction of a vehicle in the above embodiment. The wheel auto-location method further includes steps of correlating the ABS data at the one-measurement point with a specific location of a wheel based on COIN width analysis of the relevant rolling window of ABS data at the predetermined one-measurement point; and determining the specific location of the wheel where the TPM sensor parameters are assigned.

The foregoing has outlined rather broadly some exemplary embodiments along with some features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.



## BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form part of the specification and in which like numerals designate like parts, illustrate embodiments of the present invention and together with the description, serve to explain the principles of the invention. In the drawings:

FIG. **1** illustrates one embodiment of a tire pressure monitoring system;

FIG. **2** illustrates one embodiment of a wheel unit for use with the tire pressure monitoring system.

FIG. **3**A illustrates a wheel phase angle as a function of the gravitational force, i.e., acceleration and FIG. **3**B illustrates phase varying signals from different sensors.

FIG. **4** illustrates one embodiment of correlation between wheel phase angle information from the wheel unit and ABS data.

FIG. **5** is a flow chart illustrating one embodiment of a method for performing auto-location of a wheel using wheel phase angle information at the wheel unit.

FIG. **6** is a flow chart further illustrating the method for performing auto-location of the wheel at an Electronic Control Unit ("ECU").

FIG. **7** is a flow chart illustrating another embodiment of the method for performing auto-location of the wheel using wheel phase angle information.

FIG. **8** is a flow chart illustrating another embodiment of the method for performing auto-location of the wheel using wheel phase angle information.

FIG. **9** is a flow chart illustrating another embodiment of the method for performing auto-location of the wheel using wheel phase angle information.

FIG. **10**A illustrates correlation between ABS data and a one-measurement point during a rotation of a wheel and FIG. **10**B illustrates storage of the ABS data at the one-measurement point.

FIGS. **11**A-**11**D illustrate various embodiments of a phase correlation data storage event trigger based on various wheel phase angle indications.

FIG. **12** is a flow chart illustrating one embodiment of an auto-location method based on the ABS data at the one-measurement point.

FIG. **13** illustrates one embodiment of ABS tooth count values for four wheels with respect to RF transmissions from a left rear wheel unit.

FIGS. **14**A and **14**B are histograms illustrating correlated ABS tooth count values over bins.

FIG. **15** is a flow chart illustrating one embodiment of an auto-location algorithm based on a COIN width analysis.

FIGS. 16A and 16B illustrate one example of converting and storing ABS tooth counts in histogram arrays in connection with the auto-location algorithm as shown in FIG. 15.

FIG. 17 illustrates one example of a histogram array structure.

FIG. 18A illustrates a histogram having an observed confidence interval applied and FIG. 18B is a flowchart illustrating calculating a COIN width value for each histogram array in connection with the auto-location algorithm as shown in FIG. 15.

FIG. 19 illustrates a histogram array of correlated ABS tooth counts with a normal distribution curve.

FIG. 20 illustrates the boundary of the histogram array of FIG. 19 defined by the observed confidence interval.

FIGS. 21A-21D illustrate different patterns of histograms with respect to correlated ABS tooth counts of four ABS sensors for a wheel unit 101 mounted at a left front location after twenty four (24) transmissions.

FIG. 22 illustrates one example of bar charts showing COIN widths calculated for each wheel unit and each ABS sensor located at left front, right front, left rear and right rear locations.

FIG. 23 illustrates one example of configuration of COIN width margin bands.

FIG. 24 illustrates bar charts of FIG. 22 with application of the COIN width margin of FIG. 23.

FIG. 25 illustrates two examples of configurations of COIN width thresholds i.e fixed or dynamic.

FIG. 26 illustrates bar charts of FIGS. 22 and 24 with application of the fixed COIN width threshold of FIG. 25.

FIG. 27 illustrates consideration of extreme data points in connection with the COIN width analysis.

FIGS. 28A and 28B are flowcharts illustrating monitoring and detecting of rollback events.

FIG. 29A illustrates a chronological example of how a mean correlated ABS tooth count my change over time upon occurrence of rollback events during a drive, and FIG. 28B illustrates three distinct localizations of distributed correlated ABS tooth counts around three different means $\mu 1$, $\mu 2$ and $\mu 3$.

FIG. 29B illustrates a histogram applying COIN width weighting analysis.

FIG. 30 illustrates a telltale pattern of a vehicle roll, backwards, or forwards between two stop events with respect to speed and ABS tooth counts.

FIGS. 31A and 31B illustrate detecting a valid stop event.

FIGS. 32A and 32B illustrate detecting a valid move event.

FIG. 33 illustrates a histogram applying COIN width weighting analysis.

FIG. 34A illustrates one example of changes in ABS tooth count upon change of direction of left front and right front wheels and FIG. 34B is one example of a chart summarizing changes in ABS tooth counts.

FIGS. 35A and 35B illustrate enlarged view of ABS tooth rotation of left front and right front wheels for phase relationships; FIG. 35C is a chart summarizing change in ABS tooth counts.

FIG. 36 is a flow chart illustrating one embodiment of detecting and determining change of direction indication.

FIG. 37A is a flow chart illustrating one embodiment of setting up a rolling buffer of ABS data; FIG. 37B is one example structure of a rolling buffer for each wheel of a vehicle.

FIGS. 38A and 38B illustrate one embodiment of determining phase relationships prior to a stop event; FIG. 38C illustrates one embodiment of a decision matrix relating to phase relationships prior to the stop event and subsequent to a move event.

FIGS. 39A and 39B illustrate one embodiment of determining phase relationships subsequent to the move event.

FIGS. 40A and 40B illustrate one embodiment of correlating pre-stop phase relationships and post-start phase relationships and determining indication of change of direction.

## DETAILED DESCRIPTION

The present invention is directed to systems and methods in which a measurement from a wheel is combined or correlated with wheel phase and/or speed data such as antilock brake system (ABS) data to allow identification of tire pressure monitor (TPM) sensors to a specific location on a vehicle by using confidence interval analysis. In accordance with various embodiments of the present invention, a tire pressure monitoring system comprises wheel rim or tire mounted TPM sensors, typically four, and an Electronic Control unit (ECU) that receives signals from the TPM sensors. In addition, the system employs data presented to the ECU from the ABS module.

In accordance with various embodiments of the present invention, the identification of the TPM sensors may require snapshots of information at one-measurement point during a rotation of a wheel, where a snapshot is a capture of information from a short duration of a continuous stream of information. The ECU holds a rolling window of ABS data for all wheels or selected wheels associated with ABS sensors. When a radio frequency (RF) data frame is received, the ECU uses the RF data frame to store and determine relevant ABS data from the rolling window of the ABS data. An auto-location algorithm is applied to stored ABS data to identify a specific location of a wheel where a TPM sensor is arranged. The auto-location algorithm converts the correlated ABS data and stores it in memory in histogram arrays. In one embodiment, each correlated ABS tooth count per RF transmission is converted into an equivalent bin number and stored along with a number of occurrences of the same bin number in an array. The equivalent bin numbers and the number of occurrences of identical bin numbers are represented in two-dimensional histogram. For each histogram, a confidence interval width value is calculated.

It has been observed and determined through extensive testing and simulations that when correlation of RF transmissions from a wheel unit mounted at a selected wheel location and an ABS sensor mounted at the selected wheel location is plotted in a probability distribution function, it is portrayed as a normal distribution pattern about a mean value. On the other hand, a probability distribution function plotting correlation between RF transmissions from the wheel unit and ABS sensor or sensors mounted at the location other than the selected wheel location portrays a non-normal distribution, or a random distribution pattern. The confidence interval analysis takes advantage of an expected distribution shape of correlated ABS data, i.e., the normal distribution pattern or the random distribution pattern of correlated ABS data. The confidence interval analysis matches a distribution shape of actual data set with the expected distribution shape. In other words, the confidence interval analysis involves pattern-matching statistical analysis which enables association and location of each transmitting wheel unit to a respective wheel such wheel unit is mounted.

As the confidence interval analysis is based on the pattern-matching between the actual distribution shape and the expected distribution shape, it may not require measurements of absolute spread of data. Also, the confidence interval analysis may not require tracking and storing a mean value of distributions. Nor does the confidence interval analysis require a perfect normal distribution shape, as it uses the pattern matching between the actual and the expected distribution shapes. The actual random distribution shapes are significantly different from the normal distribution shape. The confidence interval analysis focuses on a highly relevant range of data rather than the entire range of data. Accordingly, the confidence interval analysis may avoid disproportional impacts on an overall analysis by extreme data points such as significantly low or high value of ABS data for a certain RF transmission in light of various nuisance factors. Extreme data points are to be expected during a regular course of driving of any vehicle. Thus, the confidence interval analysis may provide a reliable and robust technique for auto-location with high precision and accuracy.

Referring to FIGS. **1-13**, embodiments of obtaining ABS data for each RF transmission from a wheel unit are explained. FIG. **1** illustrates a tire pressure monitoring system **100** according to a first embodiment of the present invention. The system **100** is arranged in a standard vehicle **1** having four wheels. Four wheels include a left front wheel (LF), a right front wheel (RF), a left rear wheel (LR) and a right rear wheel (RR). In another embodiment, the system **100** may be arranged in any other vehicle having a different number of wheels. The system **100** includes wheel units **101**, **102**, **103** and **104** that are associated with each wheel of the vehicle **1**.

The system **100** further includes four antilock brake system (ABS) sensors **201**, **202**, **203** and **204**. In this embodiment, ABS sensors **201**, **202**, **203**, **204** are also associated with each wheel of the vehicle **1**. Accordingly, each wheel is assigned with one of the wheel units **101**, **102**, **103** and **104** and one of ABS sensors **201**, **202**, **203** and **204**. In another embodiment, ABS sensors **201**, **202**, **203**, **204** may not be associated with all four wheels. Fewer numbers of ABS sensors may be present in a structure of a vehicle such as a single axle and associated with a few selected wheels.

The system **100** also includes an Electronic Control Unit (ECU) **300** and a receiver **400**. The ECU **300** is coupled to the ABS sensors **201**, **202**, **203**, **204** via a communication bus such as a Controller Area Network (CAN) bus and receives ABS data from the ABS sensors **201**, **202**, **203**, **204**. The ECU **300** includes a processor **302** and storage **304**. The ECU **300** operates to store received ABS data in the storage **304** to provide a historic ABS trace. The ECU **300** may be implemented by any suitable means, for example a microprocessor, microcontroller, an Application Specific Integrated Circuit (ASIC), or other suitable data processing device programmed to perform the functions described herein. Further, the ECU **300** may communicate with other vehicle components using any other suitable device, either wire line or wireless. The CAN bus is an exemplary implementation of data communication among components of the vehicle. The ECU **300** stores computer program code. In one embodiment, the ECU **300** executes the computer program including instructions of calculating a first time (T**1**) based on a predetermined time delay (T**2**−T**1**), storing ABS data indicative of a wheel phase angle based on a phase correlation data storage event trigger and determining the ABS data at the first time (T**1**), and correlating a location of the wheel with a location of the ABS sensor based on a historic trace of the ABS data at the first time (T**1**).

The ECU **300** also receives data from the wheel units **101**,**102**, **103** and **104** via the receiver **400**. For example, the wheel units **101**, **102**, **103** and **104** transmit radio frequency or other wireless communications conveying data and other information to the ECU **300**. The respective wheel units include a suitable radio transmission circuit and the ECU **300** includes a suitable radio reception circuit for radio communication. Further, the radio circuits may use an agreed upon transmission and reception format and data encoding technique. The ECU **300** operates to correlate the data received from the wheel units **101**, **102**, **103** and **104** with the ABS data in order to perform auto-location, as will be discussed in detail below.

Referring to FIG. **2**, an exemplary structure of the wheel unit **101** is illustrated in more detail. The wheel units **102-104** may incorporate the same structure as that of the wheel unit **101**. As shown in FIG. **2**, the wheel unit **101** includes a microcontroller **222**, a battery **204**, a transponder coil **206**, a sensor interface **207**, a pressure sensor **208**, a wheel phase angle sensor **212**, a transmitter **214** and an antenna **216**. In other embodiments, the wheel unit **101** may have a different structure from the structure illustrated in FIG. **2**. The microcontroller **222** is coupled to the sensor interface **207**. The sensor interface **207** is coupled to the wheel phase angle sensor **212**. In one embodiment, the wheel phase angle sensor **212** measures a wheel phase angle at multiple different times. The wheel phase angle sensor **212** provides measurements to the sensor interface **207**. Alternatively, or additionally, the wheel phase angle sensor **212** provides other value or information indicative of wheel phase angle measurements. The sensor interface **207** receives the measurements of the wheel phase angle sensor **212** in the form of an electrical output signal. The sensor interface **207** receives the electrical output signal and amplifies and filters the signal. The sensor interface **207** sends the processed signal to an analog to digital converter (not shown) in order to convert the signal into a digital signal. The microcontroller **222** receives the digital form of the output signal from the wheel phase angle sensor **212** for processing.

In the illustrated embodiment, the pressure sensor **208** detects the pneumatic air pressure of the tire with which the wheel unit **101** is associated. In alternative embodiments, the pressure sensor **208** may be supplemented with or replaced by a temperature sensor or other devices for detecting tire data. An indication of the tire pressure data is sent to the microcontroller **222** via the analog-to-digital converter (not shown).

The battery **204** is a power source of the wheel unit **101**. The transponder coil **206** detects external activation of the transponder by a signal applied by a remote exciter and may modulate a signal to communicate data to a remote detector from the wheel unit **101**. The wheel unit **101** provides data including tire pressure from the pressure sensor **208** and the wheel phase angle information from the wheel phase angle sensor **212** through the transmitter **214** and the antenna **216** to the ECU **300** (see FIG. **1**).

Upon rotation of a wheel, the wheel phase angle sensor **212** operates to measure a wheel phase angle. The wheel phase angle measurements may not be against an absolute reference. The reference may be arbitrarily selected based on accuracy capability and ease of implementation or based on other criteria. In other words, the phase measurements do not have to be measured from a top of wheel, or road striking point. In this embodiment, the key piece of information may be a phase difference, or a phase delta of the wheel, and therefore, the requirement is that two different phase angles are measured relative to the same angle. Alternatively, or additionally, in another embodiment, the key piece of information may include one-measurement point during a rotation of a wheel.

The wheel phase angle sensor **212** may be mounted on a rim of the wheel, or a tire mounted sensor. Alternatively, or additionally, the wheel phase angle sensor **212** may be arranged on any suitable location associated with a wheel. In one embodiment, the wheel phase angle **212** includes a rotation sensor. For example, the rotation sensor may be a piezoelectric rotation sensor which measures a wheel phase angle based on the gravitational force. Specifically, as the wheel rotates, the gravitational force causes a sensing element of the rotation sensor to experience different forces which results in a different output signal representing a wheel phase angle or wheel angular position. In that way, the rotation sensor produces an output signal indicating a wheel phase angle at a predetermined time. The output signal of the rotation sensor may have different amplitude and/or different polarity depending on the wheel phase angle. For instance, the rotation sensor produces the output signal having amplitude M at 0 degrees and having the amplitude −M at 180 degrees. Alternatively, or additionally, any conventional rotation sensor may be used as the wheel phase angle sensor **212**.

In another embodiment, the wheel phase angle sensor **212** comprises a shock sensor of the type that produces an electrical signal in response to acceleration. The electrical signal is indicative of, or typically proportional to, the experienced change in acceleration. Alternatively, the wheel phase angle sensor **212** may each comprise an accelerometer or a microelectromechanical systems (MEMs) sensor. The main difference between an accelerometer and a shock sensor is that the output signal from a shock sensor is related to a change of force applied to the shock sensor, whereas the output signal from an accelerometer is proportional to the absolute force applied. Shock sensors may be implemented, for example, with shock sensors discussed in commonly owned U.S. Pat. No. 7,362,218, issued Apr. 22, 2008 and entitled Motion Detection Using A Shock Sensor In A Remote Tire Pressure Monitor System and commonly owned U.S. Pat. No. 7,367,227, issued May 6, 2008 and entitled Determination Of Wheel Sensor Position Using Shock Sensors And A Wireless Solution, the disclosures of which are incorporated here in its entirety. Accelerometer sensors may be implemented, for example, with sensors discussed in commonly owned U.S. Pat. No. 7,010,968, issued Mar. 14, 2006 and entitled Determination Of Wheel Sensor Position Using A Wireless Solution, the disclosure of which is incorporated here in its entirety.

In the embodiment where shock sensors or accelerometers are used as the wheel phase angle sensor **212**, FIG. **3**A is a graph illustrating a wheel phase angle or a wheel angular position as a function of the gravitational force or acceleration. In the illustrated embodiment, the wheel rotates counter clockwise, and acceleration along the z axis **304** leads acceleration along the x axis by approximately 90 degrees. The output signal is a sinusoid with a period equal to one revolution of the wheel. The magnitude of the output signal is a voltage proportional to the change in acceleration or acceleration experienced by the wheel phase angle sensor **212** such as the shock sensors or accelerometers as they rotate. The graph as shown in FIG. **3**A is by way of example, and the actual acceleration experienced in a moving wheel may be different from the amount illustrated in FIG. **3**A.

FIG. **3**B(*a*) illustrates phase varying signals output from the wheel phase angle sensor **212** which may be a shock sensor or an accelerometer. FIG. **3**B(*b*) illustrates phase varying signals output from the wheel phase angle sensor **212** which may be a Hall effect sensor, or a road striking sensor. The phase varying signals illustrated in FIG. **3**B (*a*) and (*b*) are provided to the microcontroller **222**. For example, the phase varying signals show in FIG. **3**B may be voltage signals that are converted to digital data in an analog to digital converter. The digital data may be stored and processed by the microcontroller **222**. The microcontroller **222** recognizes a repeated pattern in the phase varying signals and determines one rotation of the wheel. Then, the microcontroller **222** determines how far through the one rotation of the wheel it is at the first time (T**1**) and the second time (T**2**) and determines a first phase angle (P**1** ) and a second phase angle (P**2** ). Assuming that the phase-varying signal does not change its characteristics between the first time (T**1**) and the second time (T**2**), the first phase angle (P**1** ) and the second phase angle (P**2** ) will be relative to each other, and can be used as autolocation data.

Referring back to FIG. **2**, the sensor interface **207** is configured to provide the necessary control signals and detect the electrical signals from the wheel phase angle sensor **212** such as the shock sensor. As discussed above, the shock sensor detects change in acceleration to produce an output in the form of an electrical charge output signal. The output signal is typically in the order of 1 mV/G. Preferably, if the wheel phase angle sensor **212** includes more than one shock sensor, shock sensors can share the same interface **207** via multiplexing.

Through the sensor interface **207**, the microcontroller **222** receives output signals representing wheel phase angle from the wheel phase angle sensor **212**. The microcontroller **222** may include, for example a memory for data storage and a data processing unit. The microcontroller **222** stores a received wheel phase angle, or data related thereto, for a later transmission to the ECU **300**. The microcontroller **222** may not transmit every time the output signal has been received. In one embodiment, the microcontroller **222** calculates and determines a difference in two wheel phase angles measured by the wheel phase angle sensor **212**. For instance, the microcontroller **222** subtracts a first wheel phase angle measured at a first time (T**1**) from a second wheel phase measured at a second time (T**2**). In another embodiment, the microcontroller **222** determines the second time (T**2**) based on a predetermined known time delay (T**2**−T**1**). For instance, the microcontroller **222** may consider the first time (T**1**) as the one-measurement point of a wheel phase angle during the rotation of a wheel and the second time (T**2**) as a data transmission point of a radio frequency message as described below. The microcontroller **222** may include a clock or time base, or other circuit or module for measuring time increments and operating at specified times or during specified time durations.

The microcontroller **222** encodes and transmits a radio frequency message via the transmitter **214** and the antenna **216**. The radio frequency message includes, among other things, tire pressure information, an identifier of the wheel unit **101**, and wheel phase angle information. The wheel phase angle information may include actual wheel phase angles measured at different times. In another embodiment, the wheel phase angle information may include a wheel phase angle measured at a transmission time, such as the second time (T**2**), and a difference in wheel phase angle measured at two different times. Alternatively, the wheel phase angle information may include only the difference in wheel phase angles.

In another embodiment, the wheel phase angle information may include no actual wheel phase angle. Instead, the wheel phase angle information includes a wheel phase angle indication. As one example, the wheel phase angle indication may include a predefined function code which will trigger a phase correlation data storage event. The wheel phase angle indication may be implemented by establishing predetermined data values or patterns such as by setting a bit which is normally unused in a RF message structure (see FIG. **11**A). Alternatively, or additionally, the wheel phase angle indication may be implemented with a most significant bit, which is normally set to zero (see FIG. 11B). Additionally, the wheel phase angle indication may also include a predetermined time delay, such as T2−T1, or any other information indicative of a wheel phase angle (e.g., a pseudo-random number).

Referring again back to FIG. 1, the ECU 300 receives the radio frequency message from the wheel unit 201. The ECU 300 stores the radio frequency message, or data contained in the radio frequency message. Such data may be stored in the storage 304 which is a suitable data store such as a memory device. Also, the ECU 300 extracts the tire pressure, the identifier, and the wheel phase angle information from the radio frequency message. The ECU 300 correlates the wheel phase angle information with the ABS data from the ABS sensors 201, 202, 203, 204. In one embodiment, the ECU 300 analyzes the ABS data and determines a wheel phase angle or a wheel phase angle difference which is indicated by and corresponds to the ABS data. The ECU 300 compares the wheel phase angle information from the wheel unit 101 with the wheel phase angle or the wheel phase angle difference of the ABS data in order to determine the closest match. Upon finding the closest match, the ECU 300 assigns the identifier sent from the wheel unit 101 to a wheel whose ABS data most closely matches with the wheel phase angle information from the wheel units 101, 102, 103, 104.

In another embodiment, the ECU 300 analyzes the ABS data and determines whether the ABS data maintains a consistent value or a statistically significant trend at a predetermined time (e.g., T1). Alternatively, or additionally, the ECU 300 analyzes the ABS data and determines whether the ABS data shows a lowest standard deviation for a particular wheel location. By using this statistical correlation method, as will be described in detail below, the ECU assigns the identifier sent from the wheel unit 101 to a wheel whose ABS data is the most consistent or shows the lowest deviation, or shows a statistically significant trend.

Referring to FIG. 4, correlation of the wheel phase angle information from the wheel unit 101, 102, 103, 104 with the ABS data is further explained. In one embodiment, the wheel phase angle sensor 212 measures a wheel phase angle multiple times. In another embodiment, the wheel phase angle sensor 212 measures a wheel phase angle at the one-measurement point (e.g., T1 in FIG. 4) and does not measure the wheel phase angle at a different time (e.g., T2 in FIG. 4). In this embodiment, the wheel phase angle sensor 212 measures a first wheel phase angle (P1 ) at a first time (T1) and waits a predetermined time. The wheel phase angle sensor 212 then transmits a radio frequency message at a second time (T2) where T2=T1+Predetermined Time. The method with which the time T2−T1 is predetermined will be discussed later. Alternatively, the wheel phase angle sensor 212 measures the first wheel phase angle (P1 ) and detects the first time (T1) when the wheel phase angle reaches the first wheel phase angle (P1 ), which will be further described later. In this embodiment, the wheel units 101, 102, 103, 104 may be pre-programmed to recognize this Predetermined Time. For example, in a tire mounted TPM sensor the act of "striking" the ground provides an indication that the tire sensor has completed a revolution, relative to a previous "strike." If the TPM sensor reports the time since the last strike, then the phase of the wheel can be deduced. It may also be desirable, although not essential, that the period of the wheel revolution may also be sent.

In one embodiment, the Predetermined Time (T2−T1) may be fixed and selected to ensure multiple wheel rotations between the first time (T1) and the second time (T2). In case the difference in wheel speed between vehicle wheels may be small, setting the value of the Predetermined Time (T2−T1) to cover multiple wheel rotations may improve accuracy of the auto-location. Accordingly, a tire pressure monitoring system according to this embodiment may sufficiently comply with accuracy requirements. Alternatively, in another embodiment, a period between the first time and the second time (T1, T2) may be variable, whereas a phase angle difference or a phase delta may be fixed. This embodiment will be further explained in detail below.

As discussed in connection with FIG. 2 above, the microcontroller 222 calculates and determines a wheel phase angle difference (PD) by subtracting the second wheel phase angle (P2 ) from the first wheel phase angle (P1 ). The wheel phase angle difference (PD) may range between 0 degrees and 360 degrees. In this embodiment, the wheel units 101, 102, 103, 104 may transmit a radio frequency message including the wheel phase angle difference to the ECU 300. The wheel units 101, 102, 103, 104 may transmit the radio frequency message at a time that the wheel phase angle difference (PD) is obtained, i.e., the second time (T2). Because the wheel units 101, 102, 103, 104 provide the wheel phase angle difference (PD), the ECU 300 may reduce the burden of calculating the wheel phase angle difference. Tire pressure monitoring systems are time-critical applications, and additional time to process the calculation of the wheel phase angle difference (PD) may introduce uncertainty and increase inaccuracy.

As shown in FIG. 1, the ECU 300 periodically receives ABS data from the ABS sensors 201, 202, 203, 204. Additionally, the vehicle may include an Electronic Stability Control (ESC) system which may be the source of other inputs, such as steering angle, vehicle yaw, etc. to the ABS system information to help control vehicle progress through curves in the road. For instance, in one example the ECU 300 receives the ABS data every 40 ms. As shown in FIG. 4, a rolling window of ABS data is stored, running from the present point to a point in the past. In this embodiment, the rolling window of the ABS data is stored for each wheel throughout the entire drive. The rolling window of the ABS data is variable and large enough to contain the first time (T1). The stored ABS data provides a historic ABS trace between the first time (T1) and the second time (T2). The ABS data includes information that is used to measure a phase through which the wheel has rotated. In one embodiment, the ABS data may include a number of ABS teeth that pass through the ABS sensors 201, 202, 203, 204 during a predetermined period of time. Only as one example, 48 teeth pass through the ABS sensor 210, which indicates completion of a full cycle. The ABS data for the number of counts may be divided by the number of teeth per wheel which is constant. The remainder of the number of counts divided by the number of teeth gives an estimate of wheel angle change over any given period. Using the above example of 48 teeth, 48/48=1 and the remainder is zero. Accordingly, the ECU 300 determines that there is no wheel phase angle change.

As shown in FIG. 4, the first time (T1) and the second time (T2) may serve as time points at which correlation of wheel phase angles (P1, P2 ) with ABS data shall occur. The time delay or the time period between the first time (T1) and the second time (T2) may be predetermined in order to ensure generation of effective phase angle data and ABS data that result in accurate auto-location. The time delay or the time period between the first time (T1) and the second time (T2) may be known to the ECU 300 and the wheel units 101-104 such that the first time (T1), the second time (T2), the first phase angle (P1 ), etc. may be later calculated and determined. Alternatively, in another embodiment, the time period between the first time (T1) and the second time (T2) may be variable.

Referring to FIGS. **5**-**8**, an exemplary method for performing auto-location of a wheel using wheel phase angle information is explained in detail. FIG. **5** is a flow chart illustrating one embodiment of a method for performing auto-location of a wheel using wheel phase angle information. In particular, FIG. **5** shows operations at the wheel unit **101** for convenience. The operations at the wheel unit **101** may be equally applicable to the wheel units **102**, **103**, **104**. In the embodiment illustrated in FIG. **5**, the time period between the first time (T**1**) and the second time (T**2**) is pre-determined, whereas a phase angle difference between the first phase angle (P**1** ) and the second phase angle (P**2** ) is variable.

As shown in FIG. **5**, at the wheel unit **101**, the first wheel phase angle (P**1** ) is measured at the first time (T**1**) and the second wheel phase angle (P**2** ) is measured at the second time (T**2**) after passage of the predetermined time (Step **502**). At the wheel unit **101**, the wheel phase angle difference (PD) is calculated by subtracting P**1** from P**2** (Step **504**). The microcontroller **222** generates the radio frequency message including tire pressure, the identifier of the TPM sensor **208**, and the wheel phase angle information. The radio frequency message is transmitted via the transmitter **214** and the antenna **216** (Step **506**). The radio frequency message is transmitted a plurality of times (e.g., 5 times or 8 times) to ensure that the ECU **300** receives the message, considering clashing and path loss. Thus, interframe spacing may be introduced to avoid clashing, which occurs when two transmitters transmit at the same time so as to be indistinguishable to the receiver. (Step **520**). The same wheel phase angle information is duplicated in each frame 1 to 8. If the first frame of data is not received, then the ECU **300** must be able to calculate the time at which frame 1 was transmitted in order for the wheel phase angle data to be accurate (Step **520**). Therefore, the transmitted frames which contain the wheel phase angle information need a predetermined interframe spacing known to the ECU **300**. The frames may be numbered 1 through 8, or alternatively, the frame number information could be deduced by the ECU from the interframe spacing.

In one embodiment, the wheel phase angle information includes the first wheel phase angle (P**1** ) and the second wheel phase angle (P**2** ). The wheel unit transmits the first and the second wheel angles (P**1** and P**2** ) at the second time (T**2**) (Step **508**). In another embodiment, the wheel phase angle information includes the second wheel phase angle (P**2** ) and the wheel phase angle difference (PD) which is transmitted at the second time (T**2**) (Step **510**). In further another embodiment, the wheel phase angle information includes only the wheel phase angle difference (PD) (Step **512**).

FIG. **6** is a flow chart illustrating one embodiment of the method for performing auto-location of the wheel using wheel phase angle information at the ECU **300**. In the illustrated embodiment, the wheel phase angle difference (PD) is received at the second time (T**2**) (Step **602** and Step **512**). Here it is assumed that the ECU **300** has received the first frame. The ECU **300** calculates the first time (T**1**) based on the fixed time delay which is known to the ECU **300** (Step **604**). The first time (T**1**) may need calculation to give a reference point at which the ABS data will be analyzed. As noted above, the period between the first time (T**1**) and the second time (T**2**) is set up to ensure that a meaningful phase angle difference between the measured phase angles can be obtained.

After determining the first time (T**1**), the ECU **300** is able to calculate a phase angle difference for each ABS data per wheel between T**1** and T**2** (Step **606**). Using the example discussed above, 48 teeth of ABS teeth that have passed the period between T**1** and T**2** may indicate two full rotations of the wheel and the zero remainder of 48 teeth/24 teeth indicates zero phase angle difference. The ECU **300** compares the wheel phase angle difference (PD) against the phase angle difference for each ABS data (Step **608**). In other words, the ECU may estimate, by interpolation of the RF message phase measurement, what the number of counts from each ABS sensor would have been and search for a match from the ABS data for a wheel unit that has a similar wheel angle. The purpose of the correlation is to determine which set of ABS data matches with the deduced phase rotation of the wheel phase angle sensor **212**.

There are a number of ways to perform the interpolation. For example, linear interpolation based on the assumption that the vehicle speed is relatively constant may be used. For example, every wheel on the vehicle will rotate at least 0.1% difference in overall effective circumference. After 60 seconds at 40 kmh (typically 5.5 Hz), the difference in angular rotation of each wheel will likely be 0.001*5.5*60. This equates to ⅓ of a revolution or 120 degrees. As a result, the ECU **300** assigns the identifier to a location whose phase angle difference of ABS data mostly closely matches to the wheel phase angle difference transmitted from the wheel unit **101**.

FIG. **7** is a flow chart illustrating another embodiment of the auto-location method. In the illustrated embodiment, the wheel phase angle (P**2** ) and the wheel phase angle difference (PD) are received at the second time (T**2**) (Step **702** and Step **510**, as shown in FIG. **7**. It is assumed that the ECU **300** has received the first frame. The ECU **300** calculates the first time (T**1**) based on the fixed time delay known to the ECU **300** (Step **704**). The calculated first time (T**1**) is a reference point at which the ABS data will be analyzed. The ECU **300** further calculates wheel phase angle (P**1** ) by subtracting the wheel phase angle difference (PD) from the second phase angle (P**2** ) (Step **706**). The ECU **300** retrieves historic ABS data that is stored and determines ABS trace at the first and the second times (T**1**, T**2**)(Step **708**). Subsequently, the ECU **300** compares wheel phase angles (P**1**, P**2** ) which are transmitted from the wheel unit against ABS data at the first and the second time (T**1**, T**2**)(Step **710**). As a result, the ECU **300** assigns the identifier to a location whose phase angle difference of ABS data mostly closely matches to the wheel phase angle difference transmitted from the wheel unit (Step **712**).

FIG. **8** is a flow chart further illustrating another embodiment of the auto-location method. In the illustrated embodiment, the wheel phase angles (P**1**, P**2** ) are received at the second time (T**2**) (Step **802**), as shown in FIG. **8**, unlike the embodiments illustrated in FIGS. **6** and **7**. The ECU **300** calculates the first time (T**1**) based on the fixed time delay as the reference point (Step **804**). Subsequently, the ECU **300** retrieves stored ABS data and determines ABS trace at the first and the second times (T**1**, T**2**) (Step **806**). The ECU **300** then compares wheel phase angles (P**1**, P**2** ) which are transmitted from the wheel unit **101** against ABS data at the first and the second time (T**1**, T**2**) (Step **808**). As a result, the ECU **300** assigns the identifier to location whose phase angle difference of ABS data most closely matches to the wheel phase angle difference transmitted from the wheel unit (Step **810**).

As discussed in connection with the above-described embodiments, the wheel units **101**, **102**, **103**, **104** measure the wheel phase angle of the associated wheels LF, RF, LR and RR at two different times and determine the relative phase angle difference. The relative phase angle difference is transmitted to the ECU **300** at a later measurement time such that the relative phase angle difference is compared with similar information extracted from the ABS system. The ECU **300** will receive RF messages from the wheel units **101**, **102**, **103**, 104 including the phase angle difference and compare the phase angle difference from the wheel units **101**, **102**, **103**, **104** with the ABS data from the ABS sensors **201**, **202**, **203**, **204**. The ECU **300** periodically receives the ABS data and stores a variable rolling window of the ABS data which covers the first time (T**1**) and the second time (T**2**). Thus, the ECU **300** may estimate, by interpolation of the RF message phase measurement, what the ABS data from each ABS sensor would have been between the first time (T**1**) and the second time (T**2**) and searches for a match from the ABS data for a wheel unit that has a similar wheel angle. The purpose of the correlation is to determine which set of ABS data matches with the deduced phase angle of the wheel phase angle sensor **212**.

In the above-described embodiments, the ECU **300** determines and uses as a reference point the first and the second times T**1**, T**2** in order to perform the auto-location. The ECU **300** calculates the first time based on the second time T**2** and the fixed time delay known to the ECU **300**. The ECU **300** then determines ABS data that corresponds to the first and the second time T**1** and T**2**. In other words, the above-described embodiments rely upon the first time (T**1**) and the second time (T**2**) to define a relevant wheel phase angle and relevant ABS data for correlation. By comparing two different sets of data within the identical reference points, T**1** and T**2**, accurate correlation may be obtained. Simple and accurate implementation of correlation between the wheel phase angle information from the wheel units **101**, **102**, **103**, **104** and the ABS data may be obtained. Furthermore, the period between the first time (T**1**) and the second time (T**2**) may be easily variable to accommodate changing situations and ensure the system accuracy requirements.

Moreover, as the wheel units **101**, **102**, **103**, **104** may calculate and determine the phase angle difference, calculation burdens on the ECU **300** may be reduced. Because a tire pressure monitoring system is a time-sensitive application, reduced calculation time by the ECU **300** may increase accuracy and efficiency of such systems.

In the above-described embodiments, auto-location for determining the location of TPM sensors is performed based on the fixed time delay between the phase angle measurements and the variable phase angle difference. In another embodiment, the auto-location may also be realized by the wheel units **101**, **102**, **103**, **104** and the ECU **300** knowing a fixed phase angle difference or a fixed phase delta which will occur between variable measurements times (TD=T**2**−T**1**). In other words, the phase delta is fixed, and the period between the first time (T**1**) and the second time (T**2**), i.e., T**2**−T**1** is variable. Referring to FIG. **9**, the embodiment where the phase delta is fixed and the time period (T**2**−T**1**) is variable is explained in detail. When a wheel unit **102** decides to perform an auto-location event, the wheel unit **102** waits until it reaches a self-determined phase angle (P**1** ). The wheel unit **102** then determines the time that the self-determined phase angle (P**1** ) is reached and stores such time (T**1**) (Step **902**). In this embodiment, the wheel unit **102** is discussed only for convenience and other wheel units **101**, **103** and **104** may be equally available. After rotating through the fixed phase delta known to the wheel unit **102** and the ECU **300**, the wheel unit **102** reaches the second phase angle P**2** (P**2** =P**1** +fixed phase delta) (Step **904**). The wheel unit **102** determines the time that the second phase angle P**2** is reached and stores the time (T**2**) (Step **904**).

The wheel unit **102** transmits the identification, and Time Difference (TD=T**2**−T**1**) (Step **906**). As discussed above in conjunction with FIG. **5**, the wheel unit **102** transmits the same radio frequency message a plurality of times to ensure that the ECU **300** receives the radio frequency message (Step **908**). The ECU **300** receives the identification and the Time Difference (TD). The ECU **300** correlates the Time Difference (TD) for a known phase angle with ABS information (Step **910**). The identification is assigned to the ABS location which has swept through the fixed phase angle in the Time Difference (TD) (Step **912**). In this implementation, the fixed phase angle does not have to be an integer number of revolutions. In other words, the second phase angle (P**2** ) does not have to equal (P**1** +(N*360°), where N is an integer. The phase difference (PD) could be encoded in the transmission at T**2**, or it could be a pre-determined value which is known to both the wheel unit and the ECU.

The foregoing embodiments describe a wheel unit that transmits wheel phase angle information which includes actual measurements, a value derived from the actual measurement, etc. such as first phase angle P**1**, the second phase angle P**2**, and/or the phase angel difference (PD). The wheel phase angle information, however, is not limited to the actual measurement of the wheel phase angle and/or the phase angle difference. The wheel phase angle information may include any information indicative of, and/or translatable to a wheel phase angle. Moreover, the wheel phase angle information may include information that prompts or triggers auto-location. For example, the wheel phase angle information may include wheel phase angle indication. Receipt or detection of the wheel phase angle indication may trigger the ECU to perform a phase correlation data storage event. The ECU continuously maintains a rolling window of the ABS data. In response to the phase correlation data storage event, the ECU stores or captures relevant ABS data. In one embodiment, the wheel phase angle indication may include a predefined function code. In another embodiment, the wheel phase angle indication may include setting a bit which is normally unused in a RF message structure, or a most significant bit of a certain data byte. Alternatively, or additionally, the wheel phase angle indication may include temperature data or interframe spacings of RF transmissions.

Moreover, the foregoing embodiments compare a wheel phase angle difference with ABS data at two different times (T**1**, T**2**) to perform auto-location of a wheel. Alternatively, or additionally, the auto-location of the wheel where the TPM sensor is arranged may require a snapshot of information at one measurement point of a wheel phase angle during a rotation of the wheel, where a snapshot is a capture of information from a short duration of a continuous stream of information. The wheel unit transmits an RF message that includes or is associated with the wheel phase angle indication. The ECU holds a rolling window of wheel phase and/or speed data such as ABS data for all wheels. Upon receipt of the RF message, the ECU captures and stores a current content of the rolling window of the ABS data. Then, the ECU determines relevant ABS data from the rolling window at a predetermined time, i.e., T**1**. An auto-location algorithm is applied to the stored ABS data in order to identify the specific location of the wheel where the TPM sensor is arranged. Referring to FIGS. **10-17**, these different embodiments of the wheel auto-location system and method are described below.

FIG. **10**A illustrates the one-measurement point during the rotation of the wheel. The wheel unit **101** detects the first time (T**1**) when the wheel phase angle reaches the first phase angle (P**1** ). The first phase angle (P**1** ) is an angle of interest which may be set depending on the hardware configurations of tire pressure monitoring systems. As one example, the first phase angle (P**1** ) may be a zero-crossing point, i.e. zero, or a peak in order to facilitate efficient implementation of system hardware configurations. The first phase angle (P**1** ) is not limited to the zero-crossing point or the peak and any angle can be set as the first phase angle (P1). The wheel unit **101** is described in this embodiment by way of example, and other wheel units **102**, **103**, **104** can be used. The wheel unit **101** waits a predetermined time delay (TD=T**2**−T**1**) and transmits a RF message. In this embodiment, the controller **222** of the wheel unit **101** is programmed to know the predetermined time delay (TD). The wheel unit **101** may not measure a wheel phase angle at the second time (T**2**). Accordingly, the wheel phase angle at the second time (T**2**) is undetermined in this embodiment. In other embodiments, the wheel phase angle at the second time (T**2**) may be measured. The ABS sensors **201**, **202**, **203**, **204** transmit ABS data to the ECU **300** via the receiver **400**, as described in connection with FIG. **1** above. In another embodiment, fewer than four ABS sensors may transmit ABS data to the ECU **300**, which will be further described below.

FIG. **10**B illustrates the rolling window of the ABS data from four wheels. The ECU **300** continuously maintains the rolling window of the ABS data as shown in FIG. **10**B. The sinusoidal wave of the wheel phase angle at the first time (T**1**) and the second time (T**2**) is also shown in FIG. **10**B. The ECU **300** does not store or capture each rolling window of the ABS data. Instead, the ECU **300** responds to a phase correlation data storage event trigger and captures the current content of the rolling window of the ABS data that spans the first time (T**1**) and the second time (T**2**) as illustrated in FIG. **10**B. The phase correlation data storage event trigger will be described in detail below, referring to FIGS. **11**A-**11**D. The ECU **300** repeats this capturing or storing process multiple times until a significant number of the current contents of the ABS data is captured and stored in order to ensure reliability.

FIGS. **11**A-**11**D illustrate various embodiments of implementing the phase correlation data storage event trigger. FIGS. **11**A-**11**D also illustrate various embodiments of implementing wheel phase angle indication such that the phase correlation data storage event is triggered. FIGS. **11**A-**11**C illustrate contents of RF messages transmitted by a wheel unit and received by the ECU. Referring to FIGS. **11**A and **11**B, a first embodiment of the wheel phase angle indication is explained. In the first embodiment, an RF message **1100** contains information corresponding to wheel phase angle indication. In FIGS. **11**A and **11**B, an exemplary RF message **1100** sent from the wheel unit **101** is illustrated. The RF message includes digital data arranged in a number of data fields including, for example, a synchronization field such as a data preamble, a function code field, an identifier field, a pressure data field, a temperature data field and an error detection and correction field such as a checksum. Additional or fewer data fields may be used and the field locations in the RF message may be standardized to ensure reliable reception of the RF message. The structure of the RF message **1100** may vary depending upon vehicle hardware and/or software where this embodiment of the wheel auto-location system and method is used. In this embodiment, the function code field corresponds to the wheel phase angle indication. The function code field may be referred to as a status code field or a status byte field.

As described above, the wheel unit **101** transmits the RF message **1100** at the second time (T**2**) after the wheel phase angle reaches the first phase angle (P1) and waits the predetermined time delay (TD). The RF message **1100** may not include an actual wheel phase angle, as shown in FIGS. **11**A and **11**B. The RF message of FIG. **11**A includes a preamble, a function code **1110**, an identification of a wheel, tire pressure, temperature, and a checksum. The RF message structure including the preamble, the tire pressure, the checksum, etc. as shown in FIG. **11**A uses a conventional RF message structure. The function code **1110** may include a predefined function code which prompts or instructs the ECU **300** to trigger a phase correlation data storage event. The phase correlation data storage event indicates to the ECU **300** that a current content of a rolling window of the ABS data should be captured by the ECU **300**. As described in connection with FIG. **1** above, the ECU **300** receives ABS data from the ABS sensors **201**, **202**, **203**, **204**. The ECU **300** is continuously holding a rolling window of the ABS data which has dimensions the same or greater than the predetermined time period (TD). As shown in FIG. **10**B, the ECU **300** captures the current content of the rolling window of the ABS data in response to the phase correlation data storage event and stores it in its storage.

Referring back to FIGS. **11**A and **11**B, the function code **1110** may include a bit that has been set or changed to set to trigger the phase correlation data storage event. As one example, the bit is normally unused in a RF message structure. As another example, the bit includes two most significant bits of a certain data byte, which is normally set to zero. As shown in FIG. **11**A, the RF message **1100** sent from the wheel unit **101** includes wheel phase angle indication by adding the function code **1110**. For example, the RF message **1100** is encoded to set a bit of the function code **1110** that triggers the phase correlation data storage event. The RF message **1100** shown in FIG. **11**A includes no actual phase angle. The RF message **1100** may include the wheel phase angle indication implemented by the function code bits **1110**. The structure of the RF message **1100** has benefits of including no wheel phase angle information. This message structure having no wheel phase angle information may provide flexibility as a standard frame protocol may not need to change in order to include phase angle information.

In FIG. **11**B, the RF message **1100** may include data defining the predetermined time delay (TD=T**2**−T**1**) **1120** using a dataframe assigned to temperature data in addition to the function code bits **1110**. The predetermined time delay may represent the wheel phase angle. In another embodiment, the RF message **1100** may include a pseudo-random number that indicates or is translatable to the wheel phase angle. Various types of information which represents the wheel phase angle may be included in the RF message **1100**. For example, the wheel phase information could be encoded into 8 bits of data. This would allow a phase resolution of $360/255=1.41°$ to be realized.

Another method to provide wheel phase information is to assign a code to specific wheel phase angles. In such an exemplary embodiment, the transmitter **214** (FIG. **2**) transmits the code which corresponds to the particular phase angle of interest. In this embodiment, the ECU **300** stores a lookup table in the storage **304**. The lookup table maps the codes to actual phase angles, and the ECU **300** then deduces the phase from the transmitted code. In a further embodiment, the time delay (TD) may be one of several options known to both the wheel units **101**, **102**, **103**, **104** (FIGS. **1** and **2**) and the ECU **300**. More specifically, the wheel units **101**, **102**, **103**, **104** will transmit a short code which corresponds to one of the several options. The ECU decodes the short code, and determines which of the several options for the time delay (TD) have been used by the wheel units **101**, **102**, **103**, **104**. In a further embodiment, the wheel units **101**, **102**, **103**, **104** may encode the actual time delay (TD) value in the radio frequency transmission. For example, with a resolution of 1 millisecond and eight bits of information, a time delay of 255 milliseconds could be communicated.

Referring to FIG. **11**C, a second embodiment of the phase correlation data storage event trigger is described. FIG. **11**C illustrates an RF message that includes temperature data **1130**. In this embodiment, the temperature data **1130** includes 8 bits. As shown in FIG. **11**C, 8 bits of temperature data indicate the normal operating temperature range of the tire pressure sensor **208** (FIG. **2**). The normal operating temperature generally ranges from −40° C. to +125° C., and the temperature byte **1130** has the capability to indicate temperatures from −50° C. to +205° C. The temperatures above +125° C. may not have any practical application. Accordingly, some of the temperature bits are used to encode the wheel phase angle indication. By using the example illustrated in FIG. **11**C, the temperature of +142° C. corresponds to 11000000 and the two most significant bits of the temperature byte are 'H.' The temperature of +142° C. is well above the maximum operating temperature. The code, 11000000 may be used to trigger a phase correlation data storage event in this embodiment.

In FIG. **11**D, a third embodiment of a phase correlation data storage event trigger is illustrated. In the third embodiment, an interframe spacing among a series of RF message transmissions corresponds to the wheel phase angle indication and is used to trigger the phase correlation data storage event. In this embodiment, multiple RF message transmissions occur during the one second transmission. For instance, the identical information is transmitted eight times over a one second time period. The structure of the RF message frame, the number of RF message frames and the interframe spacings discussed in this embodiment are only by way of example and not limited thereto. The structure of the RF message frame, the number of RF message frames and/or the interframe spacings may vary.

As shown in FIG. **11**D, each interframe spacing between two consecutive RF transmissions varies. In this embodiment, 109.86 ms, 189.94 ms and 159.67 ms are respectively set as interframe spacings. The interframe spacings are encoded and known to the ECU **300**. When the ECU **300** receives the first three RF transmissions **1140**, **1145** and **1150**, the ECU **300** recognizes the interframe spacings of 109.86 ms and 189.94 ms. Then, the ECU **300** calculates when the first RF transmission **1140** is received. The time that the first RF transmission **1140** is received corresponds to the second time (T**2**). The ECU **300** subsequently calculates the first time (T**1**) and determines the ABS data at the first time (T**1**).

In FIGS. **11**A-**11**D, various embodiments of the phase correlation data storage event trigger are explained. However, the wheel auto-location method is not limited to those embodiments and other ways of implementing the phase correlation data storage event are available. As described in connection with the embodiments of FIGS. **11**A-**11**D, the ECU **300** receives or recognizes the phase correlation data storage event trigger based on the wheel phase angle indication. The ECU **300** responds to the wheel phase angle indication and performs the phase correlation data storage event. As illustrated in FIG. **10**B, the ECU **300** stores or captures the current content of the rolling window of the ABS data in response to the wheel phase angle indication. Then, the ECU **300** calculates the first time (T**1**) based on the predetermined time delay (TD) which has been known to the ECU **300**. The ECU **300** determines relevant ABS data from the ABS data stream, i.e., the stored current content of the rolling window of the ABS data relevant to the first time (T**1**). In this embodiment, the relevant ABS data corresponds to an ABS tooth count number at the first time (T**1**). The relevant ABS data is stored over time as the ECU **300** receives the RF message **1100** multiple times and repeatedly determines and stores the relevant ABS data. The ECU **300** stores the ABS data in the storage **304** and executes an auto-location algorithm that correlates the stored relevant ABS data with a specific wheel location. The auto-location algorithm is executed to identify the specific wheel location based on the trace of the relevant ABS data using a statistical correlation method.

Referring to FIG. **12**, one embodiment of an auto-location method is further explained in detail. The wheel unit **101** detects the first phase angle (P**1** ) which is set as an angle of interest at the first time (T**1**) when the first phase angle (P**1** ) is reached (Step **1210**). The first phase angle (P**1** ) is not limited to a particular angle and is set depending on system hardware configuration. Actual values of the first phase angle (P**1** ) may depend on a frequency of wheel rotation.

The wheel unit **101** waits for the predetermined time delay (TD=T**2**−T**1**) where the time delay is known to the ECU **300** (Step **1215**). The wheel unit **101** may not measure a phase angle other than the measurement at the first time (T**1**). In this embodiment, timing of one measurement, i.e., T**1** and the predetermined time delay (TD) may be indicative of the wheel phase angle. Actual phase angles of the wheel may not be used.

After waiting the predetermined time delay (TD), the wheel unit **101** transmits the RF message **1100** to the ECU **300** at the second time (T**2**) (Step **1220**). The RF message **1100** includes the wheel phase angle indication. As described above, the RF message **1100** includes predefined function code bits **1110** such that the phase correlation data storage event will be triggered by the ECU **300**.

The ECU **300** continuously maintains a rolling window of the ABS data, the window having dimensions the same or greater than the predetermined time delay (TD). The ECU **300** receives the RF message **1100** and recognizes the function code bits **1110** (Step **1225**). When the RF message **1100** includes the time delay (TD) data, the ECU **300** also recognizes such data. When the time delay (TD) data is recognized, the ECU **300** stores the current values in the rolling window of the ABS data. These current values of the rolling window will be used by the ECU **300** to perform the phase correlation data storage event upon receipt of the RF message **1100**.

The ECU **300** calculates the first time (T**1**) based on the predetermined time delay (TD) upon receipt of the RF message **1100** (Step **1230**). The ECU **300** then determines an ABS tooth count for each wheel at the first time (T**1**) (Step **1235**). The ECU **300** stores the ABS tooth count and repeats this process until a significant number of the phase correlation data storage events have occurred (Step **1240**). The stored ABS tooth count values are provided as an input to the auto-location algorithm. The output of the auto-location algorithm is the association of a wheel unit ID with a specific ABS sensor location on the vehicle.

FIG. **13** illustrates one example of the ABS tooth count values at the first time (T**1**) for all wheels which have been stored by the ECU **300**. With respect to a series of the RF transmissions from a left rear wheel unit, the ABS tooth count values at the first time (T**1**) from a left front ABS sensor are 93, 82, 18, 48, and 71 for the first five transmissions. Likewise, the ABS tooth count values at the first time (T**1**) from a right front ABS sensor and a right rear ABS sensor are 40, 23, 62, 47, 55 and 15, 57, 20, 4, 12, respectively, for the first five transmission. On the other hand, a left rear ABS sensor shows a statistically significant and consistent tooth count values, i.e., 32, 30, 29, 30, 31 at the first time (T**1**) for the first five transmissions. Even after 15 transmissions, the consistent tooth count values remain unchanged. The auto-location algorithm uses the stored ABS tooth count values as an input.

The stored ABS tooth count values as shown in FIG. **13** enable the ECU **300** to perform various statistical processing techniques. In this embodiment, the ECU **300** performs a confidence interval analysis. In other embodiments, various other processing techniques are available. A confidence interval provides a range of values which is likely to indicate the population parameter, or the population characteristics. Confidence intervals are constructed at a confidence level, such as 95% only by way of example. The confidence level of 95% works as a bracket that defines the true population parameter or characteristics in approximately 95% of cases when the same population is sampled numerous times and interval is estimated each time.

It has been observed through extensive testing and simulation that when plotted in a probability distribution function, correlation between radio frequency (RF) transmissions from a wheel-unit mounted at a wheel location and ABS tooth counts from an ABS sensor mounted at the same wheel location portrays a normal distribution pattern about a mean value. FIG. **14**A illustrates one example of the normal distribution pattern. On the other hand, FIG. **14**B illustrates one example of a distribution pattern of correlation between RF transmissions from a wheel-unit mounted at a wheel location and ABS tooth counts from an ABS sensor mounted at a different wheel location. The distribution pattern as shown in FIG. **14**B illustrates a non-normal distribution and rather, a random distribution.

Depending on a location match between a wheel unit and an ABS sensor, a distribution pattern is expected to appear as a normal distribution, or a random distribution, as shown in FIGS. **14**A and **14**B. The confidence interval analysis takes advantage of such expected shape of distribution patterns in the auto-location of a wheel unit. The confidence interval analysis is a pattern-matching statistical analysis technique which enables association and location of each transmitting wheel unit identification (ID) to a respective wheel in which it is mounted. The confidence interval analysis matches a distribution shape of actual observed data sets to an expected distribution shape, for example, a normal distribution shape, or a random distribution shape. Accordingly, the auto-location using the confidence interval analysis is different from auto-location method using conventional statistical analysis based on absolute spread of data, a standard deviation, a statistically significant value, etc. The auto-location using the confidence interval analysis may be more flexible as a pattern match between a normal distribution shape and a random distribution shape may be performed based on relative similarity rather than an absolute value. The auto-location using the confidence interval analysis may be more reliable as the confidence interval focuses on highly relevant range of data rather than infrequent and/or substantially out of range data such as extreme data points.

Referring to FIGS. **15**-**21**, embodiments of an auto-location method using the confidence interval analysis are explained in detail. FIG. **15** is a flow chart illustrating one embodiment of the auto-location method based on the confidence interval analysis. In the illustrated embodiment of the auto-location method, correlated ABS tooth counts as shown in FIG. **13** above are converted and stored in histogram arrays (Step **1502**). Referring to FIGS. **16**A and **16**B and **17**, converting and storing ABS tooth counts (Step **1502**) will be explained in detail. From each histogram array, a confidence interval (hereinafter referred to as "COIN") width value is calculated (Step **1504**). Referring to FIG. **18**, calculating the COIN width value (Step **1504**) will be explained in detail. Based on the COIN width value, the auto-location method identifies a location (Step **1506**, Step **1508**, or Step **1510**) of a wheel where a wheel unit sending RF transmission is mounted. In one embodiment, the auto-location method identifies a location of a wheel unit by assigning a wheel unit ID to the location of an ABS sensor which provides a lowest COIN width value (Step **1506**). In another embodiment, the auto-location method uses the lowest COIN width value and a COIN width margin (Step **1508**). In further another embodiment, the auto-location method uses the lowest COIN width value, a COIN width margin and/or a COIN width threshold (Step **1508**). Referring to FIGS. **22**-**26**, various embodiments of the auto-location method are explained in detail.

FIG. **16**A is a flow chart illustrating one exemplary process of converting and storing correlated ABS tooth counts in histogram arrays (Step **1502** of FIG. **15**). By way of example, correlated ABS tooth counts of the left rear (LR) ABS sensor as shown in FIG. **13** are explained. However, it would have been apparent to one of ordinary skill in the art that converting and storing correlated ABS tooth counts are not limited to the LR ABS sensor. FIG. **16**B is a diagram illustrating one example of converting LR ABS correlated tooth counts into a histogram array in conjunction with the flowchart shown in FIG. **16**A. In Step **1602**, correlated ABS tooth counts from the LR ABS sensor (see FIG. **13**) are stored for transmissions 1 to N from the wheel unit **103** as shown in a chart **1608** of FIG. **16**B. In Step **1604**, stored correlated ABS tooth counts are converted into equivalent bin numbers for transmissions 1 to N as shown in **1610** of FIG. **16**B. A number of bins used in histogram arrays can be any value. In this embodiment, a number of bins is, for example, 36 as each histogram bin represents 10 degrees of wheel rotation (i.e., 10 degrees×36=360 degrees). Each bin is used to tally the number of correlated ABS tooth counts which fall within that bin's range. For example, correlated ABS tooth counts 31-33 are converted into the bin number **12** which corresponds to the $120^{th}$ to 129th degree of the circumference of a wheel. As another example, correlated ABS tooth counts 34-35 are converted into the bin number **13** and correlated ABS tooth count **36** is converted into the bin number **14**. In Step **1606** of FIG. **16**A, a total number of converted bin counts is stored in histogram array as shown in a chart **1612** of FIG. **16**B. In other words, if the equivalent bin number **12** of correlated ABS tooth counts occurs five times based on for RF transmissions 1 to N, five (5) is stored with respect to the equivalent bin number **12**. FIG. **16**B illustrates two dimensional plotting of bin number with respect to a number of occurrences of the same bin number. For example, FIG. **16**B shows the bin number **12** on X axis and a total number of occurrences of the bin number **12**, i.e., 5 on Y axis.

FIGS. **16**A and **16**B show the correlation histogram array between correlated ABS tooth counts from the LR ABS sensor and transmissions from the wheel unit **103**. FIG. **17** illustrates a histogram array which shows all of the four wheel units **101**-**104**, all of the four ABS sensors **201**-**204** and all of the four wheel locations LF, RF, RR and LR in full scale. The bin number ranges from 0 to 35 (i.e., 36) as shown at the bottom of the histogram array. The array shown in FIG. **17** will store a number of occurrences of different bin numbers for each ABS sensor for RF transmissions **1** to N. The array shown in FIG. **17** may be readily mapped to the addressable memory space of a processor such as a microcontroller.

Now referring back to FIG. **15**, the step of calculating an actual COIN width value for each histogram array (Step **1504**) is explained in detail. FIG. **18**A illustrates an observed confidence level (CI %). The relative confidence interval width is subsequently determined. The observed confidence level represents a range of values where a confidence interval width value residing in the confidence level shows properties or characteristics of correlated ABS tooth counts accurately and reliably. As shown in FIG. **18**A, the COIN width is calculated as the distance of the horizontal axis named "angle in degrees" marked out by the confidence interval region or area. The COIN width, in degrees, equates to the distance between $\mu-x$ and $\mu+x$ where $\mu$ indicates the mean of the histogram distribution. The distribution may or may not be normal but the applied observed confidence interval is always the same value for all histograms. The mean $\mu$ of the distribution may or may not be at the center of the COIN width. The observed confidence interval is determined through extensive testing and simulating. The observed confidence interval ranges between 0% and 100% but it is typically higher. For example, the observed confidence interval is 90% in this embodiment.

FIG. **18**B is a flow chart illustrating in detail a process of calculating the COIN width value for the histogram array. As a first step (Step **1805**), an observed confidence interval (typically given as a percentage, CI %) is applied to each histogram. In this embodiment, the observed confidence interval is 90%. As a result of extensive testing and simulating, it has been determined that the observed confidence interval of 90% may substantially cover a potentially relevant and meaningful value of correlated ABS tooth counts. In a subsequent step (Step **1810**), a minimum number of bins which contain CI % of ABS tooth counts is identified from the histogram. Upon finding of the minimum number of bins, the minimum number of bins which is contained within CI % of all ABS tooth counts is multiplied by number of degrees per bin (e.g., 10 degrees) to calculate an actual COIN width (Step **1815**).

FIG. **19** illustrates a histogram of correlated ABS tooth counts with respect to the number of bins. FIG. **19** illustrates that the histogram within the COIN width shows a normal distribution curve. The histogram of ABS tooth counts does not have to exactly portray a normal distribution pattern or shape. Also, the number of correlated ABS tooth counts constituting the observed confidence interval is not required to lie within the area bounded by the normal distribution curve, between $\mu-x$ and $\mu+x$. As shown in FIG. **20**, the number of correlated ABS tooth counts need to only lie within the area bounded by the limits y1, y2, $\mu-x$ and $\mu+x$. The limit given as y2 in FIG. **19** can be any value. For example, the value of y2 is equal to 15. Based on the limits y1, y2, $\mu-x$ and $\mu+x$, data points **2010** and **2020** which are outside of the limits are not taken into consideration. The confidence interval is used to assess the width of the distribution, it is not necessary to assess the height or skewness of the distribution.

Referring back to FIG. **15** again (Steps **1506**, **1508** and **1510**) and FIG. **21**, locating wheel units is explained in detail. In Step **1506**, one embodiment of auto-location of a wheel unit is based on the location of ABS sensor which provides the lowest COIN width value. FIGS. **21**A to **21**D illustrate one example of COIN width values calculated for the wheel unit **101** with respect to four ABS sensors after 24 transmissions have been received. With respect to RF transmissions from the wheel unit **101** (LF wheel location), FIG. **21**A shows a distribution pattern of correlated ABS tooth counts from the ABS sensor **201**, FIG. **21**B shows a distribution pattern of correlated ABS tooth counts from the ABS sensor **202**, FIG. **21**C shows a distribution pattern of correlated ABS tooth counts from the ABS sensor **203**, and FIG. **21**D shows a distribution pattern of correlated ABS tooth counts from the ABS sensor **204**, as shown in FIG. **1**. FIG. **21**A shows a pattern that looks like a normal distribution pattern, as opposed to FIGS. **21**B to **21**D which show random distribution patterns. Accordingly, the auto-location method can determine that the wheel unit **101** is located at the LF location based on the pattern match as the LF ABS sensor **201** shows the normal distribution pattern. From histograms of FIGS. **21**A to **21**D, each COIN width value is calculated as the distance in degrees on the X axis within which bounds CI % of the ABS tooth counts lie. FIG. **21**A shows the lowest COIN width value, as opposed to FIGS. **21**B-**21**D showing substantially higher COIN width values.

The COIN width value is first calculated as a number of bins on the X axis as shown in FIGS. **21**A to **21**D and then converted into a value in degrees by multiplying the number of bins equal to the COIN width by the number of degrees per bin (e.g., 10 degrees in this embodiment). Preferably, a more precise COIN width value can be calculated by linearly interpolating between the number of bins which contain less than 90% of the entire data set after N transmissions and the number of bins which contain more than the number of counts required to give 90% of the entire data set after N transmissions in this embodiment. Upon finding the location of the ABS sensor which provides the lowest COIN width value, such location is identified as a location of the wheel unit. In the example as shown in FIGS. **21**A to **21**D, the LF location is identified as the location of the wheel unit.

FIG. **22** is a bar chart illustrating COIN width values which are calculated for each wheel unit **101**, **102**, **103** or **104**. For the wheel unit **101**, the bar chart shows each calculated COIN width for LF, RF, RR and LR ABS sensors. The COIN width value of the LF ABS sensor **201** is the lowest (i.e., 26) for the wheel unit **101**. Likewise, the COIN width value of the RF ABS sensor **202** is the lowest (i.e., 24) for the wheel unit **102**, the COIN width value of the RR ABS sensor **203** is the lowest (i.e., 34) for the wheel unit **103**, and the COIN width value of the LR ABS sensor **204** is the lowest (i.e., 23) for the wheel unit **104**. With respect to the wheel unit **101**, the COIN width values for three other ABS sensors **202**, **203** and **204** are significantly larger. With respect to the wheel units **102**, **103** and **104**, three other ABS sensors which are not mounted at the same wheel where the wheel unit **102**, **103** or **104** is mounted show significant COIN width values.

Referring to FIGS. **15**, **23** and **24**, another embodiment of auto-location of wheel units **101**, **102**, **103** and **104** is further described. In Step **1508** of FIG. **15**, the location of a wheel unit is identified as the location of the ABS sensor which provides the lowest COIN width value and satisfies COIN width margin criteria. FIG. **23** illustrates a wheel unit is determined to be located to an ABS sensor location if the calculated COIN width value for that ABS sensor location is smaller than the COIN width values calculated for the three other ABS sensor locations by at least a distance of an applied margin. One preferred embodiment is that the margin applied is dynamic rather than fixed and is a function of the number of correlated transmissions received from the wheel unit to be located. FIG. **23** shows examples of dynamic COIN margins, how they may change dependent on the number of correlated transmissions and how their profiles may be configurable. FIG. **23** shows 4 different COIN margin bands. The COIN margin band employed can be dependent on specific vehicle characteristics. For example, if the ABS sensor signals for a vehicle are shown to be subject to a large amount of jitter, then a more conservative COIN margin band such as band A might be employed. In that situation, the distribution of the correlated ABS tooth counts may be more spread than that of a system with no or a less amount of jitter.

FIG. **24** illustrates a bar chart showing how the COIN margin might be employed to locate wheel-units to ABS sensor locations. One axis of the bar chart shows a COIN width value and the other axis of the bar chart shows ABS sensor locations as discussed above in conjunction with FIG.

23. The COIN margin is illustrated for each wheel unit. The COIN width margin may vary for each wheel unit in this embodiment. In another embodiment, the COIN width margin may be identical for each wheel. In this embodiment, the COIN width margin for the wheel unit **101** is, for example, (**104**). As shown in FIG. **24**, for the wheel unit **101**, the COIN width value of the LF ABS sensor **201** combined with the COIN width margin (**104**) is lower than the other COIN widths. COIN width values of other ABS sensors **202**, **203** and **204** are significantly higher than the combined COIN width margin and LF COIN width value (**130**). Likewise, for the respective other wheels, the combined COIN width (lowest COIN width and COIN width margin) will be lowest for the wheel unit present at the ABS sensor location

Using the COIN width margin may improve accuracy of auto-location. In addition to the lowest value of the COIN width from a certain location of ABS sensor, the COIN width margin adds another layer of robustness in determination of the wheel location.

Referring to FIGS. **15**, **25** and **26**, another embodiment of auto-location of wheel units **101**, **102**, **103** and **104** is further described. In step **1510** of FIG. **15**, the location of a wheel unit is further defined by using a COIN width threshold. In one embodiment, the COIN width threshold may be used along with the lowest COIN width value. Alternatively, the COIN width threshold may be used along with both the lowest COIN width value and the COIN width margin criteria. FIG. **25** illustrates two examples of COIN width threshold techniques. The COIN width threshold may be fixed or dynamically changing. FIG. **26** illustrates one example of how the COIN width threshold may be used to locate wheel units to ABS sensor locations. The COIN width threshold is a predetermined value used to distinguish between the more normal data coming from wheel units mounted on the vehicle and more random data coming from wheel units not mounted to the vehicle. In order for a wheel unit to be located to a specific ABS sensor location the COIN width value for that ABS sensor location must be less than the COIN width threshold.

Using the COIN threshold may improve accuracy of auto-location. The COIN width margin and the COIN width threshold may be used interchangeably. If the lowest value of the COIN width, the COIN width margin and the COIN width threshold may be used all together, the maximum accuracy of auto-location may be achieved. It would have been apparent to one of ordinary skill in the art that the COIN width margin and threshold can be adjusted and modified in light of hardware conditions such as vehicle conditions, road conditions, and many other variables.

As the above illustrated embodiments, the COIN width value is used, instead of conventional statistical analysis. Using the COIN width may alleviate an undesirable consequence of extreme data points as shown in FIG. **27**. With the conventional statistical analysis methods, extreme data points may have a disproportionate effect. In the above embodiments, the COIN width value is used and extreme data points may not be taken into consideration especially when extreme data points are infrequent and sparse. Only data points which lie within the boundary of the observed confidence level may be considered in the calculation of the COIN width and therefore, extreme data points outside the observed confidence region will likely have no bearing on the COIN width value and the auto-location of the wheel.

As extreme data points of correlated ABS tooth value do not significantly impact the determination of the wheel location, system robustness may be optimized. Accordingly, the embodiments using the COIN width analysis may alleviate the effect that the extreme data points have on the statistical analysis to correlated tooth data of ABS sensors. The COIN width analysis may not require mean calculation and tracking the mean value of the data set under analysis, which reduces processing load and complexity. Reduced processing may be suitable for implementation in software chips having low processing power.

Referring to FIGS. **28**A and **28**B, another embodiment of COIN width analysis is described in detail. ABS tooth counts increment upwards regardless of whether a wheel is turning clockwise or counter-clockwise. Any counter clockwise movement over the course of driving may result in a shift in the perceived mean of correlated ABS tooth counts. Two events which can cause the mean of the correlated ABS tooth counts for a particular wheel to shift are as follows. The first event is that a wheel rolls backwards while the vehicle stops at a stop sign, a junction, or a traffic light, etc. Such event has been seen to be more prevalent for a vehicle with manual transmission. The second event is that a reverse maneuvering is performed via a reverse gear. The first and the second events are referred to as rollback events.

Rollback events may change means of correlated ABS tooth counts which in turn may result in incorrect auto-location. Accordingly, rollback events should be detected and managed in order to ensure that the accurate location of a wheel unit can be made. FIG. **28**A is a flow chart illustrating detecting and monitoring one example of the rollback event based on temporary stop of a vehicle in the first event. In Step **2804**, ABS tooth counts are monitored for a valid stop event. If a valid stop event has been detected, then monitoring of ABS tooth counts is performed for a valid move event (Step **2808**). If a valid move event has been detected, monitoring of ABS tooth counts is carried out until a valid stop event is detected (Step **2812**). If a second valid stop event has been detected, then it is determined that a rollback or a roll forward event has occurred (Step **2816**).

FIG. **28**B is a flow chart illustrating detecting and monitoring another example of the rollback event based on a vehicle gear state. In Step **2820**, monitoring of the vehicle gear state is performed. If a reverse gear has been engaged, then a rollback event has occurred (Step **2824**). Alternatively, if the reserve gear has been engaged, monitoring of ABS tooth counts for movement is performed (Step **2828**). Upon detection of any movement, it is determined that a rollback event has occurred (Step **2832**).

FIG. **29**A illustrates one example of detecting rollback events while a vehicle is driving. As the vehicle is driving clockwise, mean correlated ABS tooth count is stayed at 15 until T**1**. By using the example of the wheel unit **101** in FIG. **22**, upon detection of a first rollback occurrence at T**1**, mean correlated ABS tooth counts become 26. At T**2**, a second rollback occurrence takes place but mean correlated tooth count becomes 33, for example. If rollback occurrences are not taken into consideration, a larger COIN width value between t0 and tN will be considered as a relevant COIN width value. Accordingly, rollback occurrences should be considered to determine an accurate COIN width value.

FIG. **29**B illustrates one example of determining a COIN width value in the vehicle movement as shown in FIG. **29**A. Instead of considering a single composite COIN width value for correlated ABS tooth counts between t0 and tN, a first COIN width value of correlated ABS tooth counts prior to the first rollback event, a second COIN width value between the first rollback event and a second rollback event, and a third COIN width value after the second rollback event are respectively considered. That way, relevant COIN width values, without being interrupted and distracted by rollback events, may be considered and result in an accurate auto-location of wheels. Only by way of example, FIG. **29**B illustrates the histogram for the wheel **101** and ABS sensor **201** (i.e., LF location). However, it would have been apparent to one of ordinary skill in the art that this embodiment is not limited to such location.

Referring to FIGS. **30-32**, detecting valid rollback events is illustrated. FIG. **30** illustrates one example of ABS tooth counts and speed of a vehicle over time. When the vehicle stops, the speed of the vehicle drops substantially. At the same time, ABS tooth counts show irregular patterns that are different from ABS tooth counts before and after rollback events. As the vehicle resumes moving subsequent to the first stop, the speed of the vehicle increases and decreases after the second stop event. Upon occurrence of the first and the second stop events, ABS tooth counts become flat and do not increase as shown in FIG. **30**.

FIG. **31**A illustrates one example of a valid stop event. FIG. **31**B illustrates one example of an invalid stop event. During a monitoring time period of Tse, ABS tooth counts in FIGS. **31**A and **31**B show different patterns of change. In FIG. **31**A, the ABS tooth counts remain unchanged and flat for the duration of a period Tse. This signifies that a stop event has occurred. On the other hand, in FIG. **31**B, the ABS tooth counts have changed during the monitoring time period of Tse. This would not signify a stop event.

FIG. **32** illustrates one example of detecting a valid move event. FIG. **32**A illustrates one example of detecting a valid move event. During a relevant monitoring time period, if ABS tooth counts changes by Δx counts as shown in FIG. **32**A, this signifies a valid move event. On the other hand, during the relevant monitoring time period, if ABS tooth counts changes by Δy counts as shown in FIG. **32**A, this signifies an invalid move event. The amount of Δx and Δy counts may be configured in light of hardware elements such as a vehicle, ABS sensors, TPM sensors, etc. and the Δx counts are always greater than the Δy counts. By way of example only, in this embodiment, Δx has a value of 2 and Δy has a value of 1. It should also be noted that, Δy may be 0 and would signify that the ABS tooth counts have not changed and remain flat for the entire period time.

As discussed above in connection with FIG. **29**B, multiple COIN widths may be obtained during the entire drive of the vehicle as rollback events have been detected. This requires accumulating an average COIN width value for a histogram over the course of the entire drive. As shown in FIG. **33**, it is not desirable to calculate the COIN width as the COIN width value, CW4. CW4 is the entire distribution of ABS tooth counts as shown in FIG. **33**. CW4 may not properly and accurately represent the true COIN width which may result in incorrect outcome of auto-location. In this embodiment, the COIN width value may be more efficiently calculated as a weighted cumulative average of the three individual COIN widths, CW1, CW2 and CW3 through COIN width weighting.

COIN width weighting is used to calculate a weighted cumulative COIN width, CCW, which is a function of the individual COIN widths for each of the distinct distributions at μ1, μ2 and μ3, and the number of ABS tooth counts which comprise each of these distinct distributions. The number of ABS tooth counts which correspond to each of the distinct distributions μ1, μ2 and μ3 will be referred to as n1, n2 and n3, respectively. Accordingly, the weighted cumulative COIN width, CCW, is calculated as:

$$CCW=(CW1*n1+CW2*n2+CW3*n3)/(n1+n2+n3) \quad \text{(Equation 1)}$$

Calculating CCW based on Equation 1 may not require storing a mean value of correlated ABS tooth counts histograms and storing the last correlated ABS tooth count calculated. The weighted cumulative COIN width can be updated after each time a valid rollback event has been detected. By using the examples illustrated in FIGS. **29**A and **29**B, the following update can be performed.

$$\text{After time } t1,\ CCW=(CW1*n1)/n1 \quad \text{(Equation 2)}$$

$$\text{After time } t2,\ CCW=[(CCW*n1)+(CW2*n2)]/(n1+n2) \quad \text{(Equation 3)}$$

$$\text{After time } tN,\ CCW=[CCW*(n1+n2)+(CW3*n3)]/(n1+n2+n3) \quad \text{(Equation 4)}$$

Upon determination of CCW, auto-location is performed as discussed above in connection with FIGS. **15** and **21-26**. Instead of the COIN width value, CCW value is used to identify the location of the wheel. With respect to the COIN width margin and threshold, CCW value is used instead of the COIN width value. The COIN width margin and the COIN width threshold may still be applied.

In the embodiments discussed above, the COIN width analysis is used to perform auto-location of wheels. The COIN width analysis may not be affected by extreme data points which may be present for various and unknown reasons and result in an accurate outcome of auto-location. The COIN width analysis may be based on the lowest COIN with only. Alternatively, or additionally, the COIN width analysis may be based on the combination of the lowest COIN width and the COIN width margin, the lowest COIN width and the COIN width threshold, and/or the lowest COIN width, the COIN width margin and the COIN width threshold. As more COIN width related values are considered, accuracy of the auto-location may improve. It is possible to select relevant COIN width related values based on vehicle configurations, market needs, processing resources, etc. By using the COIN width analysis, more reliable and more accurate auto-location may be performed.

In addition, the COIN width analysis may not require additional hardware and is compatible with standard hardware and system configurations equipped with vehicles and vehicle manufacturing facility. As the auto-location with high precision may be performed, more upgraded and safety based functionality may be provided to vehicle manufacturers and drivers.

Now referring to FIGS. **34-40**, embodiments of a direction change indication method are described. Like the rollback events described above, the direction change of wheels may affect the COIN width analysis. The direction change indication method determines when a vehicle changes its direction from forwards to reverse or vice versa by using data from non-directional ABS sensors. Non-directional ABS sensors are ABS wheel-speed sensors which do not determine or subsequently provide information on the direction of rotation of the wheel whose speed they are measuring/sensing. Vehicle manufacturers may opt to mount non-directional ABS sensors as they tend to be less expensive than other more expensive hall-effect or directional ABS sensors which provide wheel-speed information and forwards or backwards direction information. The direction change indication method can be used to replace the roll back method as discussed above. Alternatively, the direction change indication method may be used along with the rollback detection method. In other embodiments, the direction change indication detection may be employed for any system which requires detection of a change in rotational direction of multiple wheels based on ABS data or a similar data source.

The change of direction may result in a shift in the perceived mean of correlated ABS tooth counts like rollback events discussed above. Accordingly, the change of direction may change means of correlated ABS tooth counts which in turn may result in incorrect auto-location. There is a good reason to detect and manage the change of direction to ensure that the accurate location of a wheel unit can be made.

As discussed above, ABS sensor systems output pulse counts or tooth counts. ABS sensors generate pulse counts or tooth counts for passing "teeth," magnetic poles, etc. on a wheel (or rotor or reluctor ring) connected to the vehicle's road wheels. As each of a vehicle's wheels travel at unique speeds such that the rate of angular displacement of one wheel relative to another wheel will vary over time, therefore, the instances at which ABS teeth pass a wheel speed sensor on each wheel may be used to characterize phase relationships between or among the wheels. Such phase relationships vary continuously while the vehicle is moving.

In this embodiment, ABS sensors **201**, **202**, **203** and **204** operate as the wheel speed sensor. In another embodiment, the wheel speed sensor may be arranged with each ABS sensor **201**, **202**, **203**, **204** as shown in FIG. **1**. Alternatively, one wheel speed sensor may be arranged with multiple ABS sensors. As shown in FIG. **1**, the ECU **300** may communicate with the wheel speed sensor and receive relevant data relating to change of direction correlated to ABS sensors.

To change direction, the vehicle must first come to a stop. If the vehicle is moving, then stops and starts moving again in the opposite direction, the phase relationships among wheels will be inverted. The phase relationships change constantly as the vehicle is driven due to the wheels having different rotational speeds. Therefore, the phase relationships shortly before and shortly after the stop event of a vehicle must be both analyzed to allow comparison and correlation. In embodiments described here, comparison and correlation indicate whether the direction has been changed or not and may not identify which direction the wheels have been changed.

Referring to FIGS. **34** and **35**, the principle of phase inversion for two wheels is discussed in detail. FIG. **34**A illustrates an LF wheel and an RF wheel moving in Direction A (corresponding to (i)~(vii)), stationary position (corresponding to (viii)~(xi)), and Direction B (corresponding to (xii)~(xviii)), respectively. For the stationary position, the LF and the RF wheels indicate no change of direction. As shown in FIG. **34**B, no change in tooth count of ABS sensors on the LF and the RF wheels is found. However, while the LF and the RF wheels are moving in Direction A, teeth of ABS sensor rotate and changes in tooth counts are detected as shown in FIG. **34**B (see (ii), (iii), (v) and (vi)). Likewise, while the LF and the RF wheels are moving in Direction B, teeth of ABS sensor rotate and changes in tooth counts are detected as shown in FIG. **34**B (see (xiii), (xiv), (xvi) and (xvii)).

As shown in FIG. **34**B, change of direction of wheels is associated with a predetermined pattern of ABS teeth counts. The LF and RF wheels show a pattern of "0-1-0" for the change of direction to Direction A. Likewise, the LF and RF wheels also show a pattern of "0-1-0" for the change of direction to Direction B. The significance of the pattern "0-1-0" is such that it indicates the instance where the wheel speed is slow enough that single tooth increments can be observed between ABS tooth count updates. Detection of this pattern can therefore be used to determine the last point at which phase can be characterized before a stop event and the first point at which phase can be characterized after a start event.

Referring to FIGS. **35**A, **35**B and **35**C, phase relationship between wheels upon change of direction is discussed in detail. The phase relationship includes, for example, a lead or lag relationship in this embodiment. In this embodiment, it is noted that the LF wheel leads the RF wheel before the stop event. Also in this embodiment, after the stop event, the RF wheel leads the LF wheel. FIGS. **35**A and **35**B shows two ABS toothed rings which correspond to FIG. **34**A, (vii). FIG. **35**A illustrates as if the ABS toothed rings are fixed, which appears to make the rings look stationary and make wheel speed sensors look moving for convenience of explanation and discussion. As shown in FIG. **35**A, the ABS wheel speed sensor for the LF wheel is closer in proximity to the next approaching tooth than the ABS wheel speed sensor of the RF wheel is to its next approaching tooth at the time of t0. Therefore, when moving in direction A, i.e., counter-clockwise, a change in tooth count will be observed for the LF wheel (at time T**1**) before a change in tooth count will be observed for the RF wheel (at time T**2**). In this case, the LF wheel is said to "lead" the RF wheel and conversely, the RF wheel is said to "lag" the LF wheel. It will be clear to one of ordinary skill in the art that while moving in a clockwise direction, the RF wheel will "lead" the LF wheel and the LF wheel will "lag" the RF wheel.

FIG. **35**C shows change in ABS tooth count for the counter clockwise rotation of the LF and RF wheels. The pattern of "0-1-0" is shown in the table at T**1** and T**2**. As will be described later more in detail, the pattern of change in ABS tooth count can be associated with phase relationship and change of direction indication.

FIG. **36** is a flow chart illustrating detection of direction change. For each wheel position, ABS tooth count data is stored in the rolling buffer (Step **360**). Then, in one embodiment, vehicle speed is monitored to detect whether the vehicle speed is smaller than predetermined threshold speed (Steps **362** and **364**). Alternatively, ABS data is monitored to detect a valid stop event (Step **368**) as shown above in FIGS. **28**-**30**. Upon determination of a valid stop event (Step **370**), a history trace of ABS data is retrieved and analyzed to determine a pre-stop ABS phase pattern (Step **372**). More detailed discussions on Step **372** will follow later. At Step **374**, ABS data is again monitored to detect a valid move/start event. Upon determination of a valid move/start event (Step **378**), the history trace of ABS data is analyzed again to determine a post-start ABS phase pattern (Step **380**). The change of direction is determined through comparison of pre-stop and post-start phase patterns (Step **382**).

Now each step of the detection of direction change is further explained in detail. FIG. **37** illustrates one embodiment of creating a rolling buffer of ABS data. FIG. **37**A shows a preferred embodiment where delta values are buffered. As illustrated in FIG. **37**A, a current ABS tooth value is stored as prev_abs and another current ABS tooth value is obtained as curr_abs. Then, a difference between prev_abs and curr_abs is obtained as abs_delta. Then, existing buffered data is shifted to a previous buffer element and as a result, data in a first buffer element is lost. At a next step, abs_delta is stored in the last buffer element. FIG. **37**B illustrates one embodiment of ABS data buffer of 'x' elements for four wheels, LF, RF, RR and LR wheels.

In FIG. **36**, Steps **362** and **364** are optional steps to use the vehicle speed signal to trigger Step **368**. A threshold will be applied to trigger Step **368** if the speed is low enough. Such a check may effectively decrease the burden of constantly monitoring ABS data especially when a change of direction is not feasible. A change in direction cannot be feasible unless the vehicle first comes to a standstill. Steps **368** and **370** show analysis of the ABS signal to determine when the vehicle is stopped. The "valid stop event" and "valid move event" refer to those events already described above in connection with

FIGS. **28-30**. Also, storing a history of ABS data has been described above in connection with FIGS. **4-13**.

Referring to FIGS. **38**A, **38**B and **38**C, determining the pre-stop ABS phase pattern based on the history of ABS data is explained in detail (Step **372** of FIG. **36**). FIG. **38**A illustrates one embodiment of a rolling buffer of ABS data. Upon detection of a stop event, the rolling buffer is searched backwards from the head of the buffer to determine the search window. As shown in FIG. **38**A, a pre-stop search window is defined between the detection of the stop event and a left-most side of window. To identify the pre-stop search window, a search is carried out to find a window in which the characteristic '0-1-0' is to be seen once within the ABS rolling buffer for each position.

If the pre-stop search window is identified, phases are characterized by analyzing the relationship (lead, lag or in phase) between each ABS sensor position (LF, RF, RR and LR). FIG. **38**B illustrates one example of a decision matrix for showing the lead/lag/in phase relationship among four wheels, the LF, RF, RR and LR wheels. As shown in FIG. **38**B, the LR wheel leads all three other wheels and the decision matrix shows 1, 1, and 1 for LR, RF and RR to indicate this lead relationship. For the RR wheel, it is in phase with LF and lags the RF wheel. In the decision matrix, it is marked as 0 (in phase) and −1 (lag). For the RF wheel, it leads the LF wheel which is indicated as 1.

FIG. **38**C illustrates a decision table which is constructed to satisfy all possible comparison combinations, i.e., RF phase is compared with LF phase, RR phase compared with RF (RR vs. RF) phase, etc. This continues until a lower part of the decision matrix is complete and yields 6 signed integer numbers as shown in FIG. **38**C. Likewise, an upper part of the decision matrix is complete and yields six (6) signed integer number.

Referring back to FIG. **36**, Steps **374** and **378** are discussed. After the valid stop event is detected a move event is detected. If the tooth count for any ABS position increments by "1" twice before the tooth counts for all other ABS positions have incremented once each, then the direction change may not be detectable as the phase relationship may not be entirely clearly identified. For instance, wheel spin may have occurred. Likewise, if any signal increments by more than 1 before each signal has incremented by 1, such data may not be used to consider the change of direction indication. Acceleration is too rapid to characterize.

After the valid move event has been detected, the ABS data is analyzed to characterize a post-start phase relationship (step **380**). FIGS. **39**A and **39**B illustrate one embodiment of detecting the post-start search window. As shown in FIG. **39**A, the rolling buffer of ABS data experiences the stop event and the start event. From the start event point, the ABS data is analyzed to characterize the post-start phase relationship. A search for the appropriate window of data is carried out. This time the search starts with the oldest buffered data from after the stop event and looks for a window in which all signals show the pattern of '0-1-0' once. The relative phases are assessed in the same way as Step **372**. By using the embodiment shown in FIG. **39**A, the post-start search window is identified. FIG. **39**B illustrates a decision matrix showing all possible comparison combinations including the pre-stop and the post-start search window. The decision matrix in FIG. **39**B shows six integers in the lower part and another six integers in the upper part.

Referring to FIGS. **39**B and **40**A and **40**B, one embodiment of determining change of direction through comparison of pre-stop and post-start phase patterns (Step **382** of FIG. **36**) is described in detail. As discussed above, FIG. **39**B illustrates one embodiment of the decision matrix which shows lead/lag/in phase relationships among four wheels. The lower part of the decision matrix corresponds to the pre-stop ABS data pattern and the upper part of the decision matrix corresponds to the post-start ABS data pattern. As shown in FIG. **40**A, the comparison results of the pre-stop and post-start events are correlated to determine change of direction. FIG. **40**A shows that the pre-stop figure for RF wheel, i.e., "1" is correlated with the post-start figure for RF wheel, "−1." Likewise, the pre-stop number, "0" for the RR wheel is correlated with the post-start number, "0" and the same correlation continues for the LR wheel. The correlated numbers are multiplied and the results of each multiplication are populated in the upper part of a second decision matrix as shown in FIG. **40**B. All six elements in the upper part of the second decision matrix in FIG. **40**B are summed, and the sign and magnitude of the result are used to indicate the confidence or certainty that a change of direction has occurred.

The sign of the summed result indicates three different decisions. First, a negative value, i.e., a value less than zero indicates a change of direction. Second, a positive value, i.e., a value greater than zero indicates that the direction has remained the same. Third, a value of zero yields no possibility to determine if a change in direction has in fact occurred. The magnitude of the summer result indicates the magnitude of certainty that a direction change has occurred. For instance, "−6" indicates that the direction before and after the stop are different with maximum certainty. The summed value, "0" means that data may be inconclusive. The summed value, "6" indicates that the direction before and after the stop are the same with maximum certainty. In this embodiment, the sum of the six elements is "−5" as shown in FIG. **40**B. Therefore, in this embodiment, the summed result, "−5" indicates a change of direction with a high degree of confidence.

As discussed in the above embodiments, instances at which teeth or magnetic poles on a wheel pass a wheel speed sensor arranged on each wheel may be used to characterize phase relationships between and among the wheels. The phase relationships includes, for example, lead, lag, or in phase relationships. For instance, a tooth of a LF wheel may pass the wheel speed sensor earlier than a tooth of a RF wheel while LF and RF wheels are moving counter-clockwise, and it is characterized that the LF wheel leads the RF wheel. It is also characterized that the RF wheel lags the LF wheel. Such lead/lag/in phase relationship can be recorded in a rolling buffer of ABS data as a predetermined pattern. In one embodiment, the predetermined pattern includes "0-1-0." The teeth count in the rolling buffer is relatively small as the vehicle comes to a stop in order to change direction.

Prior to a stop and after a start, a history trace of ABS data sensor is analyzed. In particular, a pre-stop and a post-start search windows are identified from the rolling buffer of ABS data sensor. It is searched to identify the predetermined pattern, such as "0-1-0." Once the pre-stop and the post-start search window are identified, a decision matrix is formed that indicates lead/lag/in phase relationship among wheels. The decision matrix records lead relationship as "1", lag relationship "−1" and in phase relationship "0". In a vehicle having four wheels, the pre-stop relationship among four wheels generates six numbers indicating phase relationships before the pre-stop. Likewise, the post-start relationship generates six numbers indicating phase relationship after the vehicle starts moving. After the decision matrix identifies and records the phase relationships among the wheels, the pre-stop and the post-start phase relationships are correlated with each other. In one embodiment, the correlation may be performed by multiplying numbers indicating the pre-stop and the post-start phase relationships. In other embodiments, various other calculation or processing methods other than the multiplication are available. The decision matrix numbers may be summed, subtracted, multiplied or divided to, from or by one another in order to attain values pertaining to how likely a change of direction has occurred. It is important to evaluate whether or not the values in the upper and lower triangle compliments differ. Fuzzy logic may be applied to determine this.

Each multiplication results in 1, 0, or −1 and such resulting numbers are summed. The sign and magnitude of the summed result are analyzed. The negative sign indicates a change of direction and the magnitude closer to "6" indicates higher certainty or confidence. On the other hand, the positive sign indicates the same direction maintained and "0" indicates inconclusive data. Based on the above, a final decision of whether a change of direction has occurred or not can be made.

The embodiments of detecting change of direction do not require any special or additional hardware. The embodiments use wheel speed sensors arranged on wheels and monitor phase relationships among wheels by checking teeth passing the wheel speed sensors. Detecting the change of direction can be associated with confidence or certainty, so reliable detection may be achieved. Detecting the change of direction can be used along with embodiments of the rollback detection, or separately.

Upon detection of change of direction as discussed above, the wheel auto-location is performed as discussed in connection with the rollback detection as shown in FIG. **29** to FIG. **33**. In other words, as change of direction is detected, multiple COIN widths may be obtained during the entire drive of the vehicle. This requires accumulating an average COIN width value for a histogram over the course of the entire drive. As shown in embodiments illustrated in FIG. **33** above, the COIN width value is calculated as a weighted cumulative average such as three individual COIN widths, CW1, CW2 and CW3 through COIN width weighting whenever the change of direction has been detected (Equations 1-4).

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

We claim:

**1**. A method for determining a change of direction of a vehicle, comprising:

maintaining a rolling window of ABS anti-lock brake system ("ABS") data indicative of an ABS tooth count and capturing a relevant rolling window of the ABS data at a predetermined one-measurement point;

storing the rolling window of the ABS data indicative of the ABS tooth count in a buffer;

monitoring the ABS data and detecting a valid stop event based, at least in part, on detecting a rate of change of the ABS tooth count substantially decrementinq to zero;

monitoring the ABS data and detecting a valid move event based, at least in part, on detecting the rate of change of the ABS tooth count substantially incrementing from zero;

determining a pre-stop phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately prior to the valid stop event;

determining a post-start phase relationship between the at least two wheels based on the ABS tooth count stored in the buffer immediately subsequent to the valid move event; and

correlating the pre-stop phase relationship and the post-start phase relationship to determine the change of direction.

**2**. The method of claim **1**, wherein the step of determining the pre-stop phase relationship comprises identifying a pre-stop search window with respect to the ABS tooth count stored in the buffer.

**3**. The method of claim **2**, wherein the step of identifying the pre-stop search window comprises identifying a predetermined pattern of the ABS tooth count for each wheel.

**4**. The method of claim **3**, wherein the predetermined pattern of the ABS tooth count comprises zero (0)-one (1)-zero (0).

**5**. The method of claim **1**, wherein the step of determining the post-start phase relationship comprises identifying a predetermined pattern of the ABS tooth count for each wheel and the predetermined pattern comprises zero (0)-one (1)-zero (0).

**6**. The method of claim **1**, wherein the step of determining the post-start phase relationship comprises identifying one of lead, lag and in phase relationship between the two wheels.

**7**. The method of claim **1**, wherein the step of determining the pre-stop phase relationship comprises:

upon determination that a first wheel leads a second wheel, recording "**1**" in a decision matrix table;

upon determination that the first wheel lags the second wheel, recording "**-1**" in the decision matrix table; and

upon determination that the first wheel is in phase with the second wheel, recording "**0**" in the decision matrix table.

**8**. The method of claim **7**, wherein the step of determining a post-start phase relationship comprises:

upon determination that the first wheel leads the second wheel, recording "**1**" in a decision matrix table;

upon determination that the first wheel lags the second wheel, recording "**-1**" in the decision matrix table; and

upon determination that the first wheel is in phase with the second wheel, recording "**0**" in the decision matrix table.

**9**. The method of claim **8**, wherein the step of correlating comprises:

multiplying a recorded value of the pre-stop phase relationship for a pair of wheels with a recorded value of the post-start phase relationship for the pair of wheels.

**10**. The method of claim **1**, wherein:

the step of determining the pre-stop phase relationship comprises recording a pre-stop value corresponding to lead, lag, or in phase relationship for each pair of wheels;

the step of determining the post-start phase relationship comprises recording a post-start value corresponding to lead, lag, or in phase relationship for each pair of wheels; and the step of correlating comprises:

multiplying the pre-stop value and the post-start value for each pair of wheels; summing each multiplication result; and determining the change of direction based on a sum of all multiplication results.

**11**. The method of claim **10**, wherein the step of determining the change of direction further comprises:

determining the change of direction when the sum of all multiplication results is a negative value;

and determining no change of direction when the sum of all multiplication results is a positive value.

**12**. The method of claim **11**, wherein the step of determining the change of direction further comprises:

determining a confidence level based on an absolute magnitude of the sum of all multiplication results.

**13**. The method of claim **12**, wherein the confidence level indicates a maximum certainty when the absolute magnitude of the sum of all multiplication results is six for four wheels.

**14**. A wheel auto-location method, comprising:

receiving a radio frequency ("RF") transmission indicating a predetermined one-measurement point during rotation of a wheel and tire pressure monitor ("TPM") sensor parameters;

calculating the predetermined one-measurement point based on the RF transmission;

maintaining a rolling window of ABS data and capturing a relevant rolling window of ABS data at the predetermined one-measurement point;

monitoring the ABS data and detecting a valid stop event based, at least in part, on detecting a rate of change of the ABS tooth count substantially decrementinq to zero;

monitoring the ABS data and detecting a valid move event based, at least in part, on detecting the rate of change of the ABS tooth count substantially incrementing from zero;

determining a pre-stop phase relationship between at least two wheels based on the ABS tooth count stored in the buffer immediately prior to the valid stop event;

determining a post-start phase relationship between the at least two wheels based on the ABS tooth count stored in the buffer immediately subsequent to the valid move event;

correlating the pre-stop phase relationship and the post-start phase relationship to determine a change of direction;

correlating the ABS data at the one-measurement point with a specific location of a wheel based on confidence interval ("COIN") width analysis of the relevant rolling window of ABS data at the predetermined one-measurement point; and

determining the specific location of the wheel where the TPM sensor parameters are assigned, and determining a confidence level of the wheel location based, at least in part, on the determined change of direction.

**15**. The wheel auto-location method of claim **14**, further comprising:

calculating a COIN width based on the ABS tooth count until an indication of the change of direction is determined; and

calculating a weighted cumulative COIN width based on individual COIN width calculations and the count of the ABS tooth count used in each COIN width calculation at the time of indication of each change of direction.

**16**. A tire pressure monitoring system for performing auto-location of a wheel in a vehicle, comprising:

a wheel unit to be associated with a wheel of the vehicle, the wheel unit comprising:

a tire pressure monitor ("TPM") sensor that measures TPM sensor parameters of the wheel; and

a wheel phase angle sensor that detects an angle of interest (P**1**) at a first time (T**1**);

wherein the wheel unit transmits at a second time (T**2**) a radio frequency (RF) message comprising:

an identification of the TPM sensor; and

measured TPM sensor parameters; and

an electronic control unit ("ECU") of the vehicle in communication with the wheel unit and an anti-lock brake system ("ABS") sensor; and

computer program code operable in conjunction with the ECU of the vehicle, the ECU in communication with the wheel unit and the ABS sensor of the vehicle, wherein in response to a phase correlation data storage event trigger, the ECU is operable in response to the computer program code to execute instructions of:

calculating the first time (T**1**) based on a predetermined time delay (T**2**-T**1**), wherein the predetermined time delay is equal to a difference between T**2** and Tl;

storing a count of a number of ABS teeth which represents the number of ABS teeth that have passed each ABS sensor in a given period of time and is indicative of wheel phase angle based on the phase correlation data storage event trigger and determining the count of the number of ABS teeth or data at the first time (T**1**);

correlating a location of the wheel with a location of the ABS sensor based on a confidence interval ("COIN") width value calculated from the count of the number of ABS teeth at the first time (T**1**); and

associating the TPM sensor parameters with the determined location of the wheel;

wherein the ECU is further operable to execute instructions of:

calculating a width based on the number of ABS teeth upon detection of an indication of a change of direction; and

calculating a weighted cumulative width based on individual COIN width value calculations and the count of the number of ABS teeth used in each COIN width value calculation at the time of indication of each change of direction.

**17**. The system of claim **16**, wherein the ECU is further operable to execute instructions of:

determining a pre-stop phase relationship between at least two wheels based on the count of the number of ABS teeth stored in a buffer immediately prior to a valid stop event;

determining a post-start phase relationship between the at least two wheels based on the count of the number of ABS teeth stored in the buffer immediately subsequent to a valid move event; and

correlating the pre-stop phase relationship and the post-start phase relationship to determine the change of direction.

**18**. The system of claim **17**, wherein the instruction of determining the pre-stop phase relationship comprises recording a pre-stop value corresponding to lead, lag, or in phase relationship for each wheel;

the instruction of determining the post-start phase relationship comprises recording a post-start value corresponding to lead, lag, or in phase relationship for each wheel; and the instruction of correlating comprises:

multiplying the pre-stop value and the post-start value for each wheel;

summing each multiplication result; and

determining the change of direction based on a sum of all multiplication results.

**19**. The system of claim **18**, wherein the instruction of determining the change of direction further comprises:

determining the change of direction when the sum of all multiplication results is a negative value; and determining no change of direction when the sum of all multiplication results is a positive value.

**20**. The system of claim **19**, wherein the instruction of determining the change of direction further comprises:

determining a confidence level based on an absolute magnitude of the sum of all multiplication results.

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